UNIVERSITY
OF FLORIDA
LIBRARIES

1853

Digitized by the Internet Archive
in 2011 with funding from
LYRASIS Members and Sloan Foundation

http://www.archive.org/details/mechanicalproper00wang

The
Mechanical
Properties
# of Wood

The Mechanical Properties of Wood

FREDERICK F. WANGAARD
Associate Professor of Forest Products
Yale University

JOHN WILEY & SONS, INC., NEW YORK
CHAPMAN & HALL, LIMITED, LONDON

ARCHI-
TECTURE
BOOK ROOM

Copyright, 1950
BY
JOHN WILEY & SONS, INC.

All Rights Reserved

This book or any part thereof must not be reproduced in any form without the written permission of the publisher.

PRINTED IN THE UNITED STATES OF AMERICA

Preface

Although intended primarily as a textbook for students of wood technology and forest utilization, this book has been written with the hope that it may also find use as a source of information for others desiring a knowledge of the technical properties of wood. In serving this objective, comprehensive tables presenting fundamental strength and related properties for more than one hundred and fifty American woods as well as tables of recommended basic and working-stress values for structural species have been incorporated in the text. Examples illustrating the derivation and application of stress values are provided.

The treatment of certain phases of the text, especially those dealing with factors affecting the strength of wood and with working stresses and the basis for grading rules for structural lumber, has been made as complete as possible in the space available. An attempt has been made to avoid unnecessary technical language and descriptions, so that it may be understood by all those interested in wood.

The preparation of this book was suggested by Dean George A. Garratt whose work of the same title, published in 1931, is well known in the field of wood technology. Although the present publication is based on Garratt's *Mechanical Properties of Wood*, subsequent developments in timber mechanics and timber engineering and the increase in knowledge relating to the effects of various factors on the properties of wood have necessitated extensive revision. The arrangement and method of treatment of its predecessor are retained, but the presentation of much of the subject matter is entirely new.

Part 1 deals with stress and strain relationships of wood, an appreciation of which is essential to an understanding of its mechanical behavior. Much of the discussion in this section is elementary mechanics of materials in general, although it is written with special reference to wood. Stresses in compression,

3-28-51 Publ. Architecture

tension, and shear are discussed with emphasis on the development of stresses in beams and their relationship to bending moment and moment of inertia. Detailed tables of the strength properties of all commercially important American woods in both the unseasoned and air-dry conditions are included.

Part 2 is concerned with factors affecting the mechanical properties of wood. These have been segregated into two main groups, namely, defects and factors other than defects. Throughout the discussion an attempt has been made to point out as clearly as possible the relation of the various factors to the serviceability of wood and to emphasize the importance of the determinable factors, such as density, moisture content, and the major defects, in the selection of material for exacting strength requirements. Many new illustrations of defects have been incorporated. Among the factors covered in this section are the effect on the quality of wood of growing conditions, position in tree, heartwood and sapwood, season of cutting, method of seasoning, and preservative treatment.

Part 3 is devoted to working stresses for structural lumber, although, broadly considered, it deals with principles that underlie the correct use of wood for a multitude of purposes in which its strength properties are involved. The significance and application of the several factors that are introduced in adjusting laboratory test data to actual service conditions, in order to insure the safe and efficient use of wood in construction, are considered for structural grades of lumber conforming to the basic requirements of American Lumber Standards. New tables of basic stresses as recently revised by the Forest Products Laboratory and of working stresses for stress-grade lumber as recommended by the National Lumber Manufacturers Association are included. The principle of strength ratios underlying the establishment of working stresses is discussed. Tables showing the relationship between defects of varying size or degree and strength ratios permit estimation of the weakening effect of knots, cross grain, checks, etc., upon any load-bearing member. Appropriate examples of the application of working stresses in determining safe loads are contained in this section.

Part 4 describes currently recommended methods of timber testing. These are for the most part the methods used by the Forest Products Laboratory and conform to the revised standard procedures for the testing of small clear specimens adopted in 1948 by the American Society for Testing Materials. In laboratories equipped with the necessary testing facilities, the instructions may be used as a manual in the conduction of mechanical tests.

The Appendix contains a sample working plan for testing small clear specimens of wood. This plan conforms to that followed by the Forest Products Laboratory in its extensive investigations covering the mechanical properties of woods grown in the United States and prescribed as standard by the American Society for Testing Materials.

A list of references has been included at the end of each part of the book. No attempt has been made to present a complete bibliography of any subject, and, for the most part, only the more general and readily available publications have been listed. The more specific references have been referred to in footnotes throughout the text.

The writer acknowledges his indebtedness to Dean Garratt for his encouragement to undertake the preparation of this book and for the many portions of the former text that have been freely used. Special thanks are also due to the Forest Products Laboratory to which the writer is grateful for supplying many of the illustrations, and for the data and other information developed at that institution during the past thirty-eight years, without which the writing of this text would have been impossible.

Acknowledgment is also made to the American Society for Testing Materials for permission to use a number of illustrations and to the National Lumber Manufacturers Association, the United States Department of Commerce, and the Aeronautical Board for the use of data appearing in their publications. Finally the writer wishes to thank the many others who have contributed in various ways to the preparation of the manuscript.

Frederick F. Wangaard

New Haven, Connecticut
December 1949.

Contents

PART 1. THE BASIC MECHANICAL PROPERTIES OF CLEAR WOOD

Page
Introduction 1
Fundamental Considerations and Definitions 3
The Structural Axes of Wood 8
Tensile Strength 9
Compressive or Crushing Strength 27
Shearing Strength 35
Strength as a Beam 38
  Stresses in Beams 41
  Failures in Beams 48
  Kinds of Loads 52
  Application of Loads 55
  Strength of Wood as a Beam 64
Stiffness 66
Toughness: Shock-Resisting Ability 68
Hardness 71
Cleavage Resistance 72
Elastic Properties of Wood 73
References 75

PART 2. FACTORS AFFECTING THE MECHANICAL PROPERTIES OF WOOD

Defects 78
  Knots 78
  Checks and Shakes 83
    Formation of Checks 84
    Formation of Shakes 96
    Effect of Checks and Shakes on Strength 97
  Cross Grain 98
    Spiral Grain 100
    Diagonal Grain 103
    Measurement of Cross Grain 104
    Effect of Cross Grain on Strength 105
  Wood-Inhabiting Fungi 107
    Decay 109
    Requirements for Decay 111

Page
Wood-Staining Fungi 115
Molds 116
Effect of Decay and Sap Stain on Strength 117
Compression Failures and Cross Breaks 120
Compression Wood 122
Pitch Pockets and Pitch 125
Pitch Pockets 126
Pitch and Pitch Streaks 129
Miscellaneous Seasoning Defects 131
Insect Injuries 134
Insect Holes 134
Minor Insect Injuries 137
Bird Peck 139
Marine Borer Injury 140
Parasitic Plant Injuries 144
Frost Injuries 145
Lightning Rings 146
Burls 147
Floccosoids 148
Indented Rings 148
Red Radial Streak in Spruce 149
Pith 149
Wane 151
Factors Other Than Defects 152
Density 152
Estimation of Density 158
Position in Tree 167
Age of Tree 170
Conditions of Growth 170
Microstructure of Wood 178
Moisture Content 179
Relation of Moisture Content to Strength of Wood 183
Effect of Method of Drying on Strength 187
Temperature 188
Preservative Treatment 191
Heartwood and Sapwood 196
Live versus Dead Timber 200
Season of Cutting 201
Duration of Stress 203
Fatigue 204
References 204

PART 3. WORKING STRESSES FOR STRUCTURAL LUMBER

Introduction 206
Factors Concerned in the Derivation of Basic Stresses 207
Variation in Strength of Clear Wood 208

Page
Duration of Load 210
Accidental Overloading 212
Basic-Stress Values for Clear Wood 212
Extreme Fiber Stress in Bending 215
Compression Perpendicular to the Grain 216
Compression Parallel to the Grain 217
Maximum Horizontal Shear 218
Modulus of Elasticity 218
Effect of Duration of Load on Basic-Stress Values 219
The Basis for Structural Lumber Grades 220
Classification of Structural Lumber 221
Standard Dimensions 222
Basic Provisions for Grading Rules for Structural Lumber 223
Strength Ratios 235
Limitations on Defects in Structural Lumber Grades 236
Working Stresses by Lumber Grades 246
Duration of Load 247
Condition of Exposure 247
Application of Working Stresses in Design 254
Beams 254
Fiber Stress in Bending 254
Horizontal Shearing Stress 262
Deflection 264
Columns 268
Short Columns 268
Intermediate Columns 269
Long Columns 270
Laminated Construction 272
Tension Parallel to Grain 273
Combined Bending and Axial Loads 273
Compression at an Angle to Grain 274
Shearing Stress in Joint Details 275
References 275

PART 4. TIMBER TESTING

Working Plan 278
Forms of Material Tested 278
Size of Specimens in Relation to Purposes of Test 279
Moisture Determination 280
Machines for Static Tests 282
Speed of Testing Machine 285
Description of Tests 286
Static Bending—Large Beams 286
Static Bending—Small Beams 293
Impact Bending 299
Compression Parallel to Grain 304

Page
Compression Perpendicular to Grain 309
Hardness 312
Shear Parallel to Grain 314
Tension Perpendicular to Grain 317
Cleavag 318
Tension Parallel to Grain 319
Toughness Test 321
Other Tests 339
References 340

APPENDIX

Nomenclature of American woods 349
Sample working plan for tests on small clear specimens of wood 353
Index 369

PART 1

The Basic Mechanical Properties of Clear Wood

INTRODUCTION

The mechanical or strength properties of wood measure its fitness and ability to resist applied or external forces. By external force is meant any force outside of a given piece of material that tends to alter its size or shape or deform it in any manner. Deformation may also be brought about by forces acting entirely within a piece, such as are set up in wood by changes in its moisture content, but these forces are concerned chiefly with physical properties of wood other than those strictly pertaining to strength. It is largely the mechanical properties that determine the fitness of wood for structural or building purposes and innumerable other uses, of which furniture, vehicles, implements, and tool handles are but a few common examples. In fact, there is hardly a single use for wood that does not depend, at least to some degree, on one or more of its strength properties.

Knowledge of the mechanical properties of wood is obtained through experimentation, either by means of service tests involving the use of the material under actual conditions met with in practice, or by laboratory experiments requiring the use of special testing apparatus. From the standpoint of general efficiency, however, laboratory tests, if properly conducted, are decidedly to be preferred. For one thing, they are more economical of time and material than service determinations and hence far better adapted to the extensive testing that must be carried on in studying the natural variation in wood. Further, it is possible in laboratory experiments to establish standard methods of testing, as well as to express the results obtained in defined units, thus affording a practical means of comparing different kinds of wood and also making it possible to specify definite sizes of material for given uses. With laboratory methods it is also possible to control most of the disturbing factors that may seriously affect the results obtained in service tests.

One of the principal objectives of laboratory investigations is to determine values per unit area for the various strength properties of wood. These, however, because of the complex structure of wood, cannot have a constant value that will be exactly repeated in each test, even though no error be made. The most that can be accomplished is to find average values, the amount of variation above and below this average, and the laws that govern the variation.

The mechanical properties of wood considered in this book are: (1) tensile strength, (2) compressive or crushing strength, (3) shearing strength, (4) bending strength, (5) stiffness, (6) toughness, or shock-resisting ability, (7) hardness, and (8) resistance to cleavage. In connection with these, associated properties of importance are briefly treated. Other properties, not discussed in this text, may also be of importance in certain uses of wood.

The term *strength* is sometimes used in its broad sense, to include all the mechanical properties of wood. More often, however, in comparing different species of wood, this general term is applied when only certain of the properties are involved. The unqualified use of the term in the latter limited sense is unfortunate and commonly leads to confusion, since any two uses of wood may involve entirely different properties. In every case the term should be so modified as to denote the specific property or use involved, as strength as a column, bending strength, stiffness, or compressive strength perpendicular to the grain.

In making use of figures indicating the various mechanical properties of wood for the purpose of comparing the relative merits of different species, the fact should be borne in mind that there is a considerable variability in each kind of wood and that small differences, such as a few hundred pounds in values of 10,000 pounds, cannot be considered as a criterion of the quality of the timber. In testing material of the same species and grade, occasional differences as great as two to one are found in the specific gravity of individual specimens, with corresponding related differences in the strength properties. The figures given in the tables in this text should not be taken as fixed values, but rather as the best estimate of the true averages, and as applicable to a large number of pieces collectively and not necessarily to individual sticks.

FUNDAMENTAL CONSIDERATIONS AND DEFINITIONS

Study of the mechanical properties of a material is concerned mostly with its behavior in relation to stresses and strains, and the factors affecting this behavior. A **stress** is a distributed force and may be defined as the mutual action (1) of one body on another or (2) of one part of a body on another part. In the first case the stress is *external;* in the other *internal.* The same stress may be internal from one point of view and external from another. An external force is always balanced by the internal stresses when the body is in equilibrium.

If no external forces act on a body, its particles assume certain relative positions, and it has what is called its *natural shape and size.* If sufficient external force is applied, the natural shape and size will be changed. This distortion or deformation of the material is known as the **strain.** Every stress produces a corresponding strain, and within a certain limit (see *proportional limit,* page 5) the strain is directly proportional to the stress producing it.[1] The same intensity of stress does not, however, produce the same strain in different materials or in different qualities of the same material. No strain would be produced in a perfectly rigid body, but such is not known to exist.

Stress is measured in pounds (or other unit of weight or force) per unit area. Stress is expressed by the relationship P/A in which P is the applied load and A is the area supporting the load. For instance, if a load (P) of 1000 pounds is uniformly supported by a vertical post with a cross-sectional area (A) of 10 square inches, the resultant compressive stress is 100 pounds per square inch.

Strain is measured in inches (or other linear unit) and is frequently expressed as strain per unit of length. Thus, if a post 10.00 inches long (L) before compression is 9.99 inches long under the compressive stress, the total strain (l) is 0.01 inch, and the strain per unit of length is $l/L = 0.01/10.00 = 0.001$ inch per inch of length.

---

[1] This is in accordance with the discovery made in 1678 by Robert Hooke, and is known as *Hooke's law.*

As the stress increases there is a corresponding increase in the strain. This ratio may be graphically shown by means of a diagram or curve plotted with the increments of load or stress as ordinates and the increments of strain as abscissas. This is known as the **stress–strain diagram.** Within the limit mentioned previously the diagram is a straight line (see Fig. 1). If the results of similar experiments on different specimens are plotted to the same scale, the diagrams furnish a ready means for comparison. The greater the resistance a material offers to deformation, the steeper or nearer the vertical axis will be the modulus line.

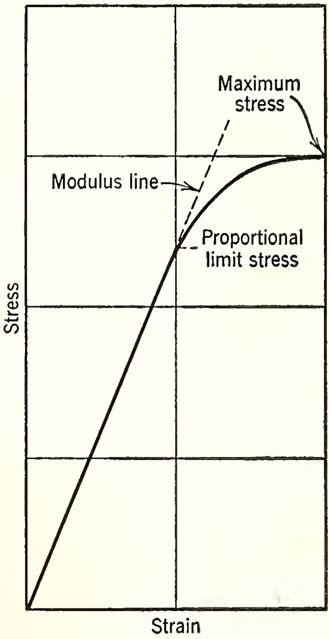


Fig. 1. Typical stress–strain diagram for wood under endwise compression.

There are three kinds of internal stresses, namely: (1) **tensile,** (2) **compressive,** and (3) **shearing.** When external forces act on a bar in a direction such as to pull it apart, the stress is a tensile stress; when exerting a direct thrust tending to shorten the member, a compressive stress. In the first instance the strain is an *elongation;* in the second a *shortening.* Whenever the forces tend to cause one portion of the material to slide on another adjacent to it, the action is called *shear.* The action is that of an ordinary pair of shears. When riveted metal plates slide on each other, the rivets are sheared off.

These three simple stresses may act together, producing compound stresses, as in flexure or bending. When a bow is bent, there is a compression of the fibers on the inner or concave side and an elongation of the fibers on the outer or convex side. There is also a tendency of the various fibers to slide past one another in a longitudinal direction, producing a shearing stress. If the bow were made of two or more separate pieces of equal length, it would be noted on bending that slipping occurred along the surfaces of contact and that the ends would no longer be even (see Fig. 7). If these pieces were securely glued together, they would no longer slip, and the restraint of such movement would induce shearing stress. Moreover, it would be found in the latter case that the bow would be much harder to bend than when the pieces were not glued together—in other words, the *stiffness* of the bow would be materially increased.

Stiffness is the property by means of which a body acted on by external forces tends to retain its natural size and shape or resists deformation. Thus a material that is difficult to bend or otherwise deform is stiff. In contrast to this, a material that has the capacity for bending a great deal without breaking is said to be *flexible.* Flexibility is not the exact counterpart of stiffness, however, as it also involves toughness and pliability.

If successively larger loads are applied to a body and then removed, it will be found that at first the body completely regains its original form on release from the stress—in other words, the body possesses *elasticity.* No substance known is perfectly elastic, though many are practically so under small loads. Rubber is an outstanding example of an elastic material, whereas wood is elastic within relatively narrow limits of strain. Eventually, as loading is continued, a point will be reached where the recovery of the specimen is incomplete. This point is known as the **proportional limit** (also termed the *elastic limit*), which may be defined as the limit beyond which it is impossible to carry the distortion of a body without producing a permanent alteration in shape. Once this limit has been exceeded, the size and shape of the specimen after removal of the load will not be the same as before, and the difference or amount of change is known as the **permanent set.** Proportional limit, as measured in tests and used in design, may also be defined as that stress per unit area at which the deformation begins to increase at a faster rate than the applied load. In practice the proportional limit of a material under test is determined from the stress–strain diagram. It is that point on the diagram where the sloping line begins perceptibly to curve (see Fig. 1).

The stress set up in a specimen by loading it to the proportional limit is known as the **fiber stress at proportional limit.** This is the maximum stress to which the material can be subjected under a given type of load without being permanently deformed.

Resilience is the amount of work done on a body in deforming it. Within the proportional limit it is also a measure of the potential energy stored in the material and represents the amount of work the material would do on being released from a state of stress. This may be graphically represented by a diagram in which the abscissas represent the amount of deflection and the ordinates the force acting. The area included between the stress–strain curve and the horizontal axis represents the work done (see Fig. 17). If the deformation is expressed in inches and the force in pounds, the result is expressed in inch-pounds.[2] If the proportional limit is taken as the apex of the triangle, the area of the triangle will represent the **elastic resilience,** or *work to proportional limit,* of the specimen. This amount of work can be applied repeatedly under a given loading without injury to the specimen. Beyond the proportional limit, the work done in deforming a body always exceeds the work given back by the body when the deforming force is removed, since a certain amount is expended in producing permanent deformation and in other ways. *Work to maximum load,* together with that to proportional limit, serves in part, to indicate the combined bending strength and toughness of a material.

Permanent set is due to the *plasticity* of the material. A perfectly plastic substance would have no elasticity, and the smallest forces would cause a set. Lead and moist clay are nearly plastic, and wood possesses this property to a greater or lesser extent. The plasticity of wood is increased by wetting, heating, and especially by steaming and boiling. Were it not for this property, it would be impossible to dry wood without destroying completely its cohesion, owing to the irregularity of shrinkage.

A substance that can undergo little change in shape without breaking or rupturing is said to be **brittle.** Chalk and glass are common examples of brittle materials. The word **brash** is used to describe this condition in wood. A brash wood breaks suddenly with a clean instead of a splintery fracture and without warning. It is not satisfactory for uses that involve shock or sudden application of load.

The measure of the stiffness of wood is termed the **modulus of**

---

[2] An **inch-pound** is the amount of work required to raise one pound a distance of one inch.

elasticity. It is the ratio of stress per unit of area to the deformation per unit of length

$$\left(E = \frac{\text{stress per unit area}}{\text{strain per unit length}}\right).$$

Modulus of elasticity is a value indicative of stiffness, not of strength, and applies only to conditions within the proportional limit. It is approximately the same whether derived from tests in compression parallel to grain or from static-bending tests.[3] Numerically, it is the load required to stretch a piece of material one inch square in cross section to twice its original length, provided it is not stressed beyond the proportional limit. Since it is impossible to fulfill this condition, this method of conceiving the modulus of elasticity is theoretical. A more practical means of visualizing the modulus of elasticity may be furnished by another example. A 1-by-1-inch square stick of wood with a modulus of elasticity parallel to grain of 1,000,000 pounds per square inch would be increased in length by 1/1,000,000 of its original length when subjected to a tension load of one pound. Within the proportional limit, increases in length resulting from other loads would be proportionate to this. Corresponding decreases in length would result from equivalent compressive loads.

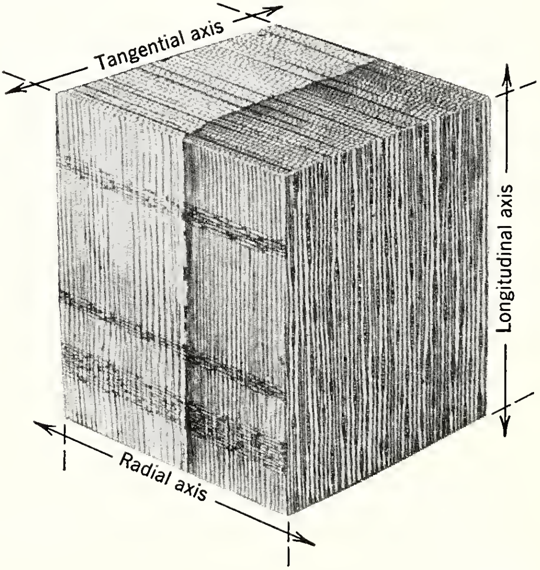
A high modulus of elasticity indicates a stiff material. Thus in unseasoned wood tested in static bending it varies from 640,000 pounds per square inch for northern white cedar, and 560,000 pounds per square inch for black willow, to 1,630,000 pounds per square inch for longleaf pine, and 1,650,000 pounds per square inch for pignut hickory. The values derived from tests of small beams in the air-dry condition are often much greater, being well over 2,000,000 pounds per square inch for some of our common woods. These values are small when compared with steel, which has a modulus of elasticity of about 30,000,000 pounds per square inch. In general, conifers rank higher in stiffness than hardwoods of the same approximate density.

---

[3] As a result of shear deformations involved in the bending of beams, modulus of elasticity as derived from tests in compression parallel to grain is usually about 10 percent higher than that calculated from static-bending tests of small beams. *Design of wood aircraft structures,* ANC Bul. 18, Army–Navy–Civil Com. on Aircraft Design Criteria, Aero. Board, Washington, 1944, p. 20.

THE STRUCTURAL AXES OF WOOD

Wood differs from most materials of construction in its fundamental *orthotropic* character. Unlike materials such as steel that are essentially *isotropic,* that is, possessing the same mechanical and elastic properties in all directions, wood is characterized by three mutually perpendicular axes of symmetry. These axes correspond to the longitudinal, radial, and tangential directions of the wood structure as shown in Fig. 2. Their significance is due fundamentally to the orientation of the structural units of fibers, ray cells, and other elements of the wood. The strength and



Yale Photo

Fig. 2. Photomicrograph of a small block of western hemlock. At the top is the cross section, showing to the right the summerwood of one season's growth, and to the left the springwood of the next season. The other two sections are longitudinal and show the fibrous character of the wood. To the left is the radial section with three rays crossing it. To the right is the tangential section, on which the rays appear as vertical strings of beads. × 35.

The longitudinal axis is parallel to the direction of the fibers; the radial axis perpendicular to the fibers and parallel to the length of the wood rays; and the tangential axis perpendicular to the fibers and parallel to the end of the growth ring as seen on the cross section.

elastic properties of wood differ in these three different directions, as discussed in the following sections. In most properties, however, the major differences are denoted by strength and elastic values parallel and perpendicular to the grain, as the differences between these properties of wood in the tangential and radial directions are, in general, relatively slight.

TENSILE STRENGTH

Tension results when a force tending to pull the material apart is applied to a body. This external force is communicated to the interior, so that any portion of the material exerts a tensile force on the remainder, the ability to do so depending on the property of cohesion. The result is an elongation or stretching of the material in the direction of the applied force. The action is the opposite of compression.

Wood exhibits its greatest strength in **tension parallel to the grain,** and it is very uncommon in practice for a clear straight-grained specimen to be pulled in two lengthwise. This is due to the difficulty of making the end fastenings secure enough for the full tensile strength to be brought into play before the fastenings shear off longitudinally.[4]

When loaded in direct tension, strain is proportional to stress virtually to ultimate load and there is no well-defined proportional limit below this point. Wood is accordingly capable of only a slight amount of yield prior to ultimate failure in direct tension.

The tensile strength of wood parallel to the grain depends on the strength of the fibers and is affected not only by the nature and dimensions of the wood elements but also by their arrangement. It is greatest in straight-grained specimens with thick-walled fibers. Cross grain of any kind materially reduces the tensile strength of wood, since the tensile strength perpendicular to the grain is only a small fraction of that parallel to the grain. The ratio of tensile strength parallel to the grain to that perpendicular to the grain is commonly as high as 40 to 1.

Relatively few data are available on the true tensile strength

---

[4] Because of this difficulty tests are not usually made in tension parallel to the grain. The standard procedure for making such tests is described under Timber Testing, page 319.

TABLE 1. STATIC STRENGTH PROPERTIES OF AMERICAN WOODS IN THE GREEN CONDITION

Species	Moisture Content, %	Specific Gravity*	Static Bending						Compression Parallel to Grain, psi		Compression Perpendicular to Grain, psi	Hardness, lb.		Shear, psi	Cleavage, lb./in. of Width	Tension Perpendicular to Grain, psi
			Stress at Proportional Limit, psi	Modulus of		Work, in.-lb./in.^{3}										
				Rupture, psi	Elasticity, 1000 psi	Proportional Limit	Maximum Load	Total	Stress at Proportional Limit	Maximum Crushing Strength		End	Side			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hardwoods																
Alder, red	98	0.37	3800	6,500	1170	0.70	8.0	15.3	2620	2960	310	550	440	770	220	390
Apple	46	0.61	3600	7,400	1050	0.75	15.7	36.4	1990	3000	850	1040	1090	1640	480	900
Ash, Biltmore	42	0.51	5500	9,300	1340	1.31	11.6	27.4	3530	3980	880	950	850	1230	340	540
Ash, black	85	0.45	2600	6,000	1040	0.41	12.1	31.7	1690	2300	430	590	520	860	280	490
Ash, blue	39	0.53	5700	9,600	1240	1.47	14.7	38.2	3580	4180	990	1140	1030	1540	350	580
Ash, green	48	0.53	5300	9,500	1400	1.14	11.8	27.6	3560	4200	910	960	870	1260	350	590
Ash, Oregon	48	0.50	4200	7,600	1130	0.92	12.2	33.3	2760	3510	650	850	790	1190	310	590
Ash, pumpkin	51	0.48	4500	7,600	1040	1.08	9.4	18.4	2850	3360	990	880	750	1210	360	570
Ash, white	42	0.55	5100	9,600	1460	1.04	16.6	41.6	3190	3990	810	1010	960	1380	330	590
Aspen	94	0.35	3200	5,100	860	0.69	6.4	13.4	1670	2140	220	280	300	660	140	230
Aspen, largetooth	99	0.35	2900	5,400	1120	0.44	5.6	12.6	2020	2500	250	400	370	730	190	310
Basswood	105	0.32	2700	5,000	1040	0.40	5.3	10.3	1690	2220	210	290	250	600	150	280
Beech	54	0.56	4300	8,600	1380	0.85	11.9	30.8	2550	3550	670	970	850	1290	410	720
Beech, blue (Hornbeam, American)	48	0.58	3200	6,800	990	0.61	19.1	60.6	1420	2670	730	900	940	1160	260	350
Birch, Alaska white	58	0.49	3800	7,100	1350	0.60	11.6	32.5	2050	3030	430	550	560	920	180	200
Birch, gray	63	0.45	1800	4,900	400	0.47	13.9	37.8	1080	1860	250	430	480	..	..	..
Birch, paper	65	0.48	3000	6,400	1170	0.45	16.2	42.8	1640	2360	340	470	560	840	210	380
Birch, sweet	53	0.60	4800	9,400	1650	0.94	15.7	41.4	2680	3740	580	1070	970	1240	300	430
Birch, yellow	67	0.55	4200	8,300	1500	0.70	16.1	43.5	2620	3380	530	810	780	1110	270	430

Blackwood	42	0.83	5500	11,100	1550	1.16	12.3	39.0	3760	4940	1870	1570	1700	1370	280	660
Buckeye, yellow	141	0.33	2600	4,800	980	0.41	5.4	10.5	1680	2050	210	360	290	660	180	320
Bustic	44	0.86	5800	12,400	1860	1.00	17.1	..	3750	5330	1700	..	..	..	..	..
Butternut	104	0.36	2900	5,400	970	0.52	8.2	21.2	2020	2420	270	410	390	760	220	430
Buttonwood	47	0.69	4600	7,400	1190	1.00	6.2	15.6	3050	4110	1140	1080	1110	1220	370	470
Cascara	61	0.50	3400	6,300	630	1.04	13.4	49.7	1890	3270	670	680	730	1150	260	510
Catalpa, hardy	72	0.38	2700	5,200	840	0.51	7.9	25.1	1450	2360	320	420	410	680	220	430
Cherry, black	55	0.47	4200	8,000	1310	0.80	12.8	31.8	2940	3540	440	750	660	1130	330	570
Cherry, pin	46	0.36	2900	5,000	1040	0.47	6.2	18.3	1810	2170	260	440	390	680	170	300
Chestnut	122	0.40	3100	5,600	930	0.59	7.0	17.0	2080	2470	380	530	420	800	240	440
Chinquapin, golden	134	0.42	4200	7,000	1020	1.09	9.5	20.4	2030	3020	490	730	600	1010	230	480
Cottonwood, eastern	111	0.37	2900	5,300	1010	0.49	7.3	16.9	1740	2280	240	380	340	680	220	410
Cottonwood, northern black	132	0.32	2900	4,800	1070	0.44	5.0	12.7	1760	2160	200	280	250	600	170	270
Dogwood	62	0.64	4800	8,800	1180	1.11	21.0	49.1	..	3640	1030	1410	1410	1520	..	..
Dogwood, Pacific	52	0.58	4200	8,200	1090	0.92	17.0	38.7	2410	3640	870	1140	980	1300	340	740
Elder, blueberry	124	0.46	3400	6,600	900	0.72	8.8	30.7	2380	3040	520	760	720	1090	320	560
Elm, American (Elm, white)	89	0.46	3900	7,200	1110	0.81	11.8	29.7	1920	2910	440	680	620	1000	..	590
Elm, rock	48	0.57	4600	9,500	1190	1.05	19.8	49.9	2970	3780	750	980	940	1270	..	..
Elm, slippery	85	0.48	4000	8,000	1230	0.82	15.4	38.2	2790	3320	510	750	660	1110	380	640
Fig, golden	88	0.44	3200	5,800	600	0.92	6.6	15.2	....	2630	650	620	580	....	..	..
Gum, black (Tupelo, black)	55	0.46	4000	7,000	1030	0.91	8.0	15.3	2490	3040	600	790	640	1100	330	570
Gum, blue	79	0.62	7600	11,200	2010	1.65	13.9	38.5	4840	5250	1020	1310	1340	1550	360	640
Gum, red (Gum, sweet)	81	0.44	3700	6,800	1150	0.81	9.4	21.7	2230	2840	460	630	520	1070	330	510
Gum, tupelo (Tupelo, water)	97	0.46	4200	7,300	1050	0.98	8.3	17.5	2690	3370	590	800	710	1190	340	600

* Based upon oven-dry weight and green volume.

From L.J. Markwardt and T.R.C. Wilson, *Strength and related properties of woods grown in the United States*, U.S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

TABLE 1. STATIC STRENGTH PROPERTIES OF AMERICAN WOODS IN THE GREEN CONDITION—*Continued*

Species	Moisture Content, %	Specific Gravity*	Static Bending						Compression Parallel to Grain, psi		Compression Perpendicular to Grain, psi	Hardness, lb.		Shear, psi	Cleavage, lb./in. of Width	Tension Perpendicular to Grain, psi
			Stress at Proportional Limit, psi	Modulus of		Work, in.-lb./in.^{3}										
				Rupture, psi	Elasticity, 1000 psi	Proportional Limit	Maximum Load	Total	Stress at Proportional Limit	Maximum Crushing Strength		End	Side			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hardwoods																
Gumbo limbo	99	0.30	2000	3,300	560	0.45	3.5	4.1	930	1510	290	290	230	590	170	380
Hackberry	65	0.49	2900	6,500	950	0.58	14.5	38.2	2070	2650	490	760	700	1070	350	630
Haw, pear	63	0.62	3900	7,600	960	0.89	22.7	52.0	....	3110	980	1220	1200	1360	..	..
Hickory, bigleaf shagbark	61	0.62	5600	10,500	1340	1.36	29.9	88.0	2740	3920	1000	..	..	1190	..	..
Hickory, bitternut	66	0.60	5500	10,300	1400	1.22	20.0	75.5	4330	4570	990	..	..	1240	..	..
Hickory, mockernut	59	0.64	6300	11,100	1570	1.38	26.1	74.6	3900	4480	1000	..	..	1280	..	..
Hickory, nutmeg	74	0.56	4900	9,100	1290	1.06	22.8	58.2	3620	3980	940	..	..	1030	..	..
Hickory, pignut	54	0.66	6200	11,700	1650	1.34	31.7	86.1	3950	4810	1140	..	..	1370	..	..
Hickory, shagbark	60	0.64	5900	11,000	1570	1.28	23.7	76.4	3430	4580	1040	..	..	1520	..	..
Hickory, water	80	0.61	6000	10,700	1560	1.29	18.8	52.9	3240	4660	1090	..	..	1440	..	..
Holly	82	0.50	3400	6,500	900	0.72	10.8	26.7	2050	2640	610	860	790	1130	360	610
Honeylocust	63	0.60	5600	10,200	1290	1.40	12.6	34.4	3320	4420	1420	1440	1390	1660	490	930
Hophornbeam	52	0.63	4500	8,500	1150	1.02	13.3	39.1	2570	3570	730	1160	1170	1370	330	450
Inkwood	56	0.73	7200	10,700	1540	1.88	16.0	64.1	3310	4480	1600	1320	1440	1750	450	..
Ironwood, black (Leadwood)	32	1.04	10100	16,400	2200	2.64	12.6	37.2	5660	7570	3460	....	....	....	..	..
Laurel, California	70	0.51	3900	6,600	720	1.23	16.8	45.6	1980	3020	800	1020	1000	1270	430	780
Laurel, mountain	62	0.62	5800	8,400	920	2.03	12.5	28.6	....	4310	1110	1400	1300	1670	..	..
Locust, black	40	0.66	8800	13,800	1850	2.36	15.4	39.9	6120	6800	1430	1640	1570	1760	400	770

Madrono, Pacific	68	0.58	4700	7,600	880	1.43	11.2	22.0	2430	3320	780	1120	940	1420	430	770
Magnolia, cucumber	80	0.44	4200	7,400	1560	0.66	10.0	21.8	2810	3140	410	600	520	990	260	440
Magnolia, evergreen	105	0.46	3600	6,800	1110	0.67	15.4	34.8	2160	2700	570	780	740	1040	340	610
Magnolia, mountain	89	0.40	3400	6,100	1190	0.55	8.3	16.5	2270	2610	330	570	500	830	260	450
Mangrove	39	0.89	9700	15,200	2300	2.30	14.6	38.7	5200	6490	2460	2010	2240	1800	..	..
Maple, bigleaf	72	0.44	4400	7,400	1100	1.02	8.7	14.2	2510	3240	550	760	620	1110	320	600
Maple, black	65	0.52	4100	7,900	1330	0.70	12.8	29.8	2800	3270	740	940	840	1130	430	720
Maple, red	63	0.49	3800	7,700	1390	0.71	11.4	24.7	2360	3280	500	780	700	1150	290	..
Maple, silver	66	0.44	3100	5,800	940	0.61	11.0	22.3	1930	2490	460	670	590	1050	300	560
Maple, striped	35	0.44	3600	7,200	1080	0.68	10.9	13.4	1790	2920	500	500	..	1150	..	..
Maple, sugar	58	0.56	5100	9,400	1550	1.03	13.3	33.6	2850	4020	800	1070	970	1460	..	..
Mastic	39	0.89	7100	10,400	1580	1.79	8.1	19.8	4950	5880	2680	1670	1770	1670	430	1030
Oak, black	80	0.56	4600	8,200	1180	1.02	12.2	30.1	2720	3470	870	1000	1060	1220	..	..
Oak, bur	70	0.58	3600	7,200	880	0.89	10.7	26.1	2380	3290	840	1160	1110	1350	430	800
Oak, California black	106	0.51	3400	6,200	740	1.03	8.8	16.0	1880	2800	890	910	850	1140	350	700
Oak, canyon live	62	0.70	6300	10,600	1340	1.70	14.4	30.9	3940	4690	1480	1590	1570	1700	520	970
Oak, chestnut	72	0.57	4600	8,000	1370	0.90	9.4	22.4	2890	3520	660	970	890	1210	380	690
Oak, laurel	84	0.56	4500	7,900	1390	0.86	11.2	28.3	2650	3170	710	1020	1000	1180	380	770
Oak, live	50	0.81	8400	11,900	1580	2.54	12.3	26.0	4170	5430	2520	1670	1880	2210	550	1040
Oak, Oregon white	72	0.64	4600	7,700	790	1.51	13.7	29.8	2480	3570	1380	1430	1390	1630	450	940
Oak, pin	75	0.58	4000	8,300	1320	0.71	14.0	35.2	..	3680	880	1000	1070	1290	470	800
Oak, post	69	0.60	5000	8,100	1090	1.31	11.0	25.4	2840	3480	1060	1160	1130	1280	410	790
Oak, northern red	80	0.56	4100	8,300	1350	0.73	13.2	34.5	2360	3440	760	1060	1000	1210	430	750
Oak, Rocky Mountain white (Oak, Gambel)	61	0.62	3200	5,900	480	1.23	11.3	27.2	1330	2940	1110	1210	1280	1530	370	750
Oak, scarlet	65	0.60	4500	10,400	1480	0.81	15.0	41.9	2840	4090	1030	1170	1200	1410	420	700
Oak, southern red	90	0.52	4200	6,900	1140	0.93	8.0	16.5	2220	3030	680	910	860	930	280	480
Oak, swamp red	78	0.61	6500	10,800	1790	1.32	14.7	38.0	3820	4620	940	1270	1240	1320	460	800

* Based upon oven-dry weight and green volume.

From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

TABLE 1. STATIC STRENGTH PROPERTIES OF AMERICAN WOODS IN THE GREEN CONDITION—*Continued*

Species	Moisture Content, %	Specific Gravity*	Static Bending						Compression Parallel to Grain, psi		Compression Perpendicular to Grain, psi	Hardness, lb.		Shear, psi	Cleavage, lb./in. of Width	Tension Perpendicular to Grain, psi
			Stress at Proportional Limit, psi	Modulus of		Work, in.-lb./in.^{3}			Stress at Proportional Limit	Maximum Crushing Strength		End	Side			
				Rupture, psi	Elasticity, 1000 psi	Proportional Limit	Maximum Load	Total								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hardwoods																
Oak, swamp chestnut	76	0.60	4800	8,500	1350	1.00	12.8	32.2	3000	3540	710	1100	1110	1260	400	670
Oak, swamp white	74	0.64	5400	9,900	1590	1.05	14.5	34.7	3580	4360	940	1200	1160	1300	480	860
Oak, water	81	0.56	5600	8,900	1550	1.14	11.1	32.5	3260	3740	770	1050	1010	1240	450	820
Oak, white	68	0.60	4700	8,300	1250	1.08	11.6	28.2	3090	3560	830	1120	1060	1250	420	770
Oak, willow	94	0.56	4400	7,400	1290	0.88	8.8	21.3	2340	3000	750	1020	980	1180	400	760
Osage-orange	31	0.76	7800	13,700	1330	2.53	37.9	101.7	3980	5810	2260	1840	2040	..	..	..
Palmetto, cabbage	134	0.37	1900	3,800	480	0.45	4.0	15.8	1410	1750	190	330	280	570	110	220
Paradise tree	81	0.33	1900	3,500	700	0.40	1.8	2.4	1260	1810	260	350	240	710	150	310
Pecan	63	0.60	5200	9,800	1370	1.18	14.6	43.4	3100	3990	960	1270	1310	1480	420	680
Persimmon	58	0.64	5600	10,000	1370	1.35	13.0	31.2	3160	4170	1110	1240	1280	1470	410	770
Pigeon-plum	52	0.77	5000	9,800	1300	1.17	11.6	24.7	4260	4940	1500	1730	1720	1510	400	850
Poisonwood	71	0.51	3200	5,100	410	1.36	5.6	7.2	1220	2160	900	400	300	910	180	350
Poplar, balsam	112	0.30	2100	3,900	750	0.35	4.2	7.2	1220	1690	170	240	230	500	130	160
Poplar, yellow	64	0.38	3400	5,400	1090	0.62	5.4	8.9	1930	2420	330	390	340	740	220	450
Rhododendron, great	99	0.50	4600	6,900	870	1.38	12.1	32.4	..	3470	890	1000	860	1240	..	..
Sassafras	67	0.42	3600	6,000	910	0.80	7.1	22.2	2400	2730	460	610	520	950	300	520
Serviceberry	48	0.66	5600	9,600	1640	1.08	16.2	37.9	3250	4080	780	1250	1240	1260	400	730
Silverbell	70	0.42	3500	6,500	1160	0.62	8.8	16.1	2140	2830	430	550	470	930	280	460
Sourwood	69	0.50	4400	7,700	1320	0.82	9.8	20.0	2700	3250	680	860	730	1160	400	710

Stopper, red	41	0.81	....	15,000	1940	...	21.6	48.3	....	6140	2450	..	..	1820	..	920
Sugarberry	62	0.47	3200	6,600	810	0.78	12.0	30.7	1990	2800	580	840	740	1050	380	660
Sumach, staghorn	45	0.45	3000	5,800	810	0.67	10.8	42.4	....	2680	480	670	590	....	..	..
Sycamore	83	0.46	3300	6,500	1060	0.60	7.5	15.9	2400	2920	450	700	610	1000	330	630
Walnut, black	81	0.51	5400	9,500	1420	1.16	14.6	35.9	3520	4300	600	960	900	1220	360	570
Walnut, little	67	0.53	3400	8,000	910	0.74	12.8	46.4	....	3020	760	..	..	...	..	..
Willow, black	139	0.34	1800	3,800	560	0.36	10.8	19.8	960	1520	220	350	360	620	230	430
Willow, western black	105	0.39	3100	5,600	1020	0.58	10.8	27.6	1810	2340	330	490	500	870	210	360
Witch-hazel	70	0.56	5000	8,300	1110	1.29	19.5	56.8	....	3400	620	1010	980	1120	..	..
Softwoods																
Cedar, Alaska	38	0.42	3800	6,400	1140	0.77	9.2	26.2	2500	3050	430	540	440	840	170	330
Cedar, incense	108	0.35	3900	6,200	840	0.94	6.4	8.8	2940	3150	460	570	390	830	160	280
Cedar, Port Orford	43	0.40	4000	6,200	1420	0.65	7.4	22.8	2770	3130	350	460	400	830	100	180
Cedar, eastern red	35	0.44	3400	7,000	650	1.08	15.0	34.7	2540	3570	860	760	650	1010	180	330
Cedar, southern red	26	0.42	5000	8,400	930	1.57	8.8	10.7	3910	4360	910	810	580	1190	210	400
Cedar, western red	37	0.31	3200	5,100	920	0.63	5.0	10.1	2470	2750	340	430	270	710	140	230
Cedar, northern white	55	0.29	2600	4,200	640	0.60	5.7	8.9	1490	1990	290	320	230	620	140	240
Cedar, southern white (Cedar, Atlantic white)	35	0.31	2500	4,700	750	0.51	5.9	13.5	1660	2390	300	400	290	690	120	180
Cypress, southern (Cypress, bald)	91	0.42	4200	6,600	1180	0.91	6.6	13.9	3100	3580	500	440	390	810	180	300
Douglas fir (coast type)	36	0.45	4800	7,600	1550	0.85	6.8	19.2	3410	3890	510	510	480	930	160	240
Douglas fir (intermediate type)	48	0.41	3800	6,800	1350	0.63	6.6	13.1	2570	3300	480	510	450	840	190	300
Douglas fir (Rocky Mt. type)	38	0.40	3600	6,400	1180	0.65	6.8	13.7	2540	3000	450	450	400	880	160	350
Fir, alpine	47	0.31	2400	4,400	860	0.39	4.4	5.2	1690	2060	310	280	220	610	130	..
Fir, balsam	117	0.34	3000	4,900	960	0.52	4.7	6.9	2080	2400	210	290	290	610	130	180
Fir, corkbark	62	0.28	2500	4,200	850	0.43	4.2	5.1	1630	2010	190	280	210	600	150	300

* Based upon oven-dry weight and green volume.

From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U.S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

TABLE 1. STATIC STRENGTH PROPERTIES OF AMERICAN WOODS IN THE GREEN CONDITION—*Continued*

Species	Moisture Content, %	Specific Gravity*	Static Bending						Compression Parallel to Grain, psi		Compression Perpendicular to Grain, psi	Hardness, lb.		Shear, psi	Cleavage, lb./in. of Width	Tension Perpendicular to Grain, psi
			Stress at Proportional Limit, psi	Modulus of		Work, in.-lb./in.^{3}			Stress at Proportional Limit	Maximum Crushing Strength		End	Side			
				Rupture, psi	Elasticity, 1000 psi	Proportional Limit	Maximum Load	Total								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Softwoods																
Fir, lowland white	94	0.37	3600	6,100	1300	0.58	5.6	14.8	2640	3020	340	420	360	760	150	240
Fir, noble	36	0.35	3600	5,800	1270	0.61	6.0	14.3	2420	2740	340	330	290	750	150	230
Fir, California red	108	0.37	4100	6,000	1060	0.95	6.7	12.6	....	2830	440	390	380	920	190	340
Fir, silver	66	0.35	3500	5,700	1260	0.60	6.0	12.6	2380	2670	290	360	310	670	150	240
Fir, white	115	0.35	3800	5,700	1030	0.84	5.1	11.5	2390	2710	370	380	330	750	170	290
Hemlock, eastern	111	0.38	3800	6,400	1070	0.76	6.7	16.8	2600	3080	440	500	400	850	150	230
Hemlock, mountain	62	0.43	3800	6,600	1080	0.79	9.6	28.2	2540	3150	470	600	500	910	200	330
Hemlock, western	74	0.38	3400	6,100	1220	0.57	6.8	17.3	2480	2990	390	520	430	810	190	310
Juniper, alligator	40	0.48	3600	6,600	450	1.67	13.4	16.4	2490	3730	1030	960	820	1280	..	..
Larch, western	58	0.48	4600	7,500	1350	1.01	7.1	18.2	3250	3800	560	470	450	920	160	230
Pine, jack	105	0.39	3000	5,400	920	0.55	5.9	21.0	2180	2580	380	380	370	760	180	310
Pine, Jeffrey	101	0.37	3200	5,000	980	0.60	4.7	14.1	2050	2370	350	320	340	690	160	260
Pine, limber	68	0.37	3900	5,200	800	1.08	5.2	8.3	1850	2410	320	300	310	740	170	270
Pine, loblolly	81	0.47	4100	7,300	1410	0.68	8.2	24.2	2550	3490	480	420	450	850	180	260
Pine, lodgepole	65	0.38	3000	5,500	1080	0.49	5.6	11.9	2110	2610	310	320	330	680	150	220
Pine, longleaf	63	0.54	5200	8,700	1600	0.95	8.9	32.4	3430	4300	590	550	590	1040	210	330
Pine, mountain	75	0.49	4500	7,500	1270	0.94	8.1	25.2	2980	3540	560	480	490	960	200	320
Pine, northern white (Pine, eastern white)	68	0.34	3100	5,000	1020	0.54	5.2	10.8	2060	2490	290	310	310	660	140	240
Pine, Norway (Pine, red)	54	0.44	3700	6,400	1380	0.59	5.8	28.4	2410	3080	360	360	340	780	160	190

Pine, pitch	79	0.45	3600	6,800	1200	0.68	9.2	27.9	1950	2950	450	420	470	860	190	280
Pine, pond	56	0.50	4500	7,400	1280	0.93	7.5	26.8	2940	3660	540	460	510	940	190	280
Pine, ponderosa	91	0.38	3100	5,000	970	0.59	5.1	12.4	2070	2400	360	300	310	680	170	290
Pine, sand	36	0.45	4100	7,500	1020	0.95	9.6	20.6	2670	3440	560	460	480	1140	. .	380
Pine, shortleaf	81	0.46	3900	7,300	1390	0.63	8.2	26.1	2500	3430	440	410	440	850	200	320
Pine, slash	66	0.56	5100	8,900	1580	1.02	9.5	30.6	3040	4340	680	600	630	1000	230	400
Pine, sugar	137	0.35	3400	5,100	940	0.70	5.4	12.0	2330	2530	350	320	310	680	180	270
Pine, western white	54	0.36	3400	5,200	1170	0.56	5.0	17.9	2430	2650	290	310	310	640	160	260
Pinyon	63	0.50	2600	4,800	650	0.61	7.6	23.0	1810	2590	480	510	600	920	. .	460
Redwood (virgin)	112	0.38	4800	7,500	1180	1.18	7.4	15.2	3700	4200	520	570	410	800	170	260
Redwood (second growth, openly grown)	146	0.28	2800	4,600	640	0.68	5.1	6.3	1810	2320	310	390	280	640	160	260
Redwood (second growth, closely grown)	112	0.32	3600	6,100	1000	0.73	6.1	10.9	2840	3280	350	470	350	730	180	290
Spruce, black	38	0.38	2900	5,400	1060	0.45	7.4	20.4	1540	2570	180	430	370	660	120	100
Spruce, Engelmann	100	0.31	2500	4,200	830	0.43	4.9	6.2	1680	1980	290	250	240	590	130	. .
Spruce, red	43	0.38	3400	5,800	1190	0.58	6.9	16.2	2380	2650	340	410	350	760	150	220
Spruce, Sitka	42	0.37	3300	5,700	1230	0.53	6.3	18.3	2240	2670	340	430	350	760	150	250
Spruce, white	50	0.37	3300	5,600	1070	0.60	6.0	16.8	2130	2570	290	350	320	690	140	220
Tamarack	52	0.49	4200	7,200	1240	0.84	7.2	28.8	2930	3480	480	400	380	860	160	260
Yew, Pacific	44	0.60	6500	10,100	990	2.46	20.2	54.3	3440	4650	1040	1340	1150	1620	250	450

* Based upon oven-dry weight and green volume.

From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

TABLE 2. STATIC STRENGTH PROPERTIES OF AMERICAN WOODS AIR-DRIED TO 12 PERCENT MOISTURE CONTENT*

Species	Specific Gravity, Oven Dry Weight		Static Bending						Compression Parallel to Grain, psi		Compression Perpendicular to Grain, psi	Hardness, lb.		Shear, psi	Cleavage, lb./in. of Width	Tension Perpendicular to Grain, psi
			Stress at Proportional Limit, psi	Modulus of		Work, in.-lb./in.^{3}										
	Vol. at Test	Vol. Oven Dry		Rupture, psi	Elasticity, 1000 psi	Proportional Limit	Maximum Load	Total	Stress at Proportional Limit	Maximum Crushing Strength		End	Side			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hardwoods																
Alder, red	0.41	0.43	6,900	9,800	1380	1.85	8.4	10.7	4530	5820	540	980	590	1080	270	420
Apple	0.67	0.74	6,600	12,800	1270	2.31	23.0	43.7	3120	6030	1300	2150	1730	1740	..	..
Ash, Biltmore	0.55	0.58	9,200	13,000	1600	2.97	11.7	20.1	5670	7380	1510	1590	1140	1680	410	710
Ash, black	0.49	0.53	7,200	12,600	1600	1.57	14.9	34.4	4520	5970	940	1150	850	1570	380	700
Ash, blue	0.57	0.60	8,100	13,800	1400	2.68	14.4	31.3	5460	6980	1760	1720	1290	2030	440	..
Ash, green	0.56	0.61	8,900	14,100	1660	2.72	13.4	23.4	5120	7080	1620	1630	1200	1910	440	700
Ash, Oregon	0.55	0.58	7,000	12,700	1360	2.08	14.4	22.3	4100	6040	1540	1430	1160	1790	410	720
Ash, pumpkin	0.52	0.55	6,500	11,100	1270	1.91	8.0	15.2	3950	5690	1800	1430	990	1720	430	770
Ash, white	0.60	0.64	8,900	15,400	1770	2.60	17.6	34.8	5790	7410	1410	1720	1320	1950	480	940
Aspen	0.38	0.40	5,600	8,400	1180	1.53	7.6	15.4	3040	4250	460	510	350	850	210	260
Aspen, largetooth	0.39	0.41	5,600	9,100	1430	1.25	7.7	13.9	4090	5300	560	620	420	1080	220	390
Basswood	0.37	0.40	5,900	8,700	1460	1.37	7.2	10.1	3800	4730	450	520	410	990	230	350
Beech	0.64	0.67	8,700	14,900	1720	2.63	15.1	30.9	4880	7300	1250	1590	1300	2010	490	1010
Beech, blue (Hornbeam, American)	0.70	0.72	3,900	12,200	1080	0.77	37.1	76.7	3330	5680	2000	1620	1780	2410	680	..
Birch, Alaska white	0.55	0.59	7,700	13,600	1900	1.85	13.9	29.8	5290	7450	820	860	830	1400	370	660
Birch, gray	0.51	0.55	5,500	9,800	1150	1.46	10.8	35.3	2670	4870	920	680	760	1340	..	..
Birch, paper	0.55	0.60	6,900	12,300	1590	1.80	16.0	35.9	3610	5690	740	890	910	1210	540	..
Birch, sweet	0.65	0.71	10,100	16,900	2170	2.72	18.0	22.4	6330	8540	1340	1960	1470	2240	640	950
Birch, yellow	0.62	0.66	10,100	16,600	2010	2.89	20.8	38.0	6130	8170	1190	1480	1260	1880	520	920

Blackwood	0.83	0.96	8,700	16,400	2090	2.03	17.9	75.3	....	8340	2360	..	..	..	..	..
Buckeye, yellow	0.36	0.38	5,100	7,500	1170	1.26	5.9	7.7	3010	4170	440	470	350	960	240	520
Bustic	0.88	..	....	....	....	..	..	..	4950	9540	..	..	..	..	..	..
Butternut	0.38	0.40	5,700	8,100	1180	1.59	8.2	15.8	4200	5110	570	570	490	1170	220	440
Buttonwood	0.71	0.85	6,800	10,200	1580	1.70	5.9	..	....	7850	1630	..	..	....	..	..
Cascara	0.52	0.55	6,000	8,700	960	2.14	7.8	..	3460	6080	1310	1240	1040	1610	..	..
Catalpa, hardy	0.41	0.42	4,700	9,400	1210	1.08	9.6	20.2	2740	4970	570	650	550	1130	300	570
Cherry, black	0.50	0.53	9,000	12,300	1490	3.11	11.4	14.2	5960	7110	850	1470	950	1700	350	560
Cherry, pin	0.39	0.42	5,700	8,500	1270	1.51	8.2	25.1	3900	4620	520	740	510	1030	230	320
Chestnut	0.43	0.45	6,100	8,600	1230	1.78	6.5	12.5	3780	5320	760	720	540	1080	250	460
Chinquapin, golden	0.46	0.48	7,900	10,700	1240	3.11	9.5	19.1	4150	5540	680	840	730	1260	..	..
Cottonwood, eastern	0.40	0.43	5,700	8,500	1370	1.39	7.4	19.4	3490	4910	470	580	430	930	270	580
Cottonwood, northern black	0.35	0.37	5,300	8,300	1260	1.25	6.7	10.8	3270	4420	370	540	350	1020	220	330
Dogwood	0.73	0.80	9,200	14,900	1530	3.10	19.5	38.9	....	7700	1920	2430	2150	2260	..	..
Dogwood, Pacific	0.64	0.70	7,200	10,500	1470	2.02	11.0	46.8	4300	7540	1650	1870	1350	1720	410	1040
Elder, blueberry	0.52	0.57	5,600	9,200	1030	1.56	9.9	..	3860	5090	760	860	840	....	..	..
Elm, American (Elm, white)	0.50	0.55	7,600	11,800	1340	2.53	13.0	33.9	4030	5520	850	1110	830	1510	..	660
Elm, rock	0.63	0.66	8,000	14,800	1540	2.45	19.2	43.1	4700	7050	1520	1510	1320	1920	..	..
Elm, slippery	0.53	0.57	7,700	13,000	1490	2.35	16.9	40.2	4760	6360	1010	1120	860	1630	340	530
Fig, golden	0.44	..	3,900	7,200	800	1.03	6.9	11.1	....	4410	....	....	..	....	..	..
Gum, black (Tupelo, black)	0.50	0.55	7,300	9,600	1200	2.54	6.2	10.6	3470	5520	1150	1240	810	1340	340	500
Gum, blue	0.74	0.80	11,400	16,600	2370	3.28	12.4	28.1	8190	9940	1720	1640	1540	1840	..	..
Gum, red (Gum, sweet)	0.49	0.53	8,100	11,900	1490	2.57	11.3	15.7	4700	5800	860	950	690	1610	380	800
Gum, tupelo (Tupelo, water)	0.50	0.52	7,200	9,600	1260	2.41	6.9	11.5	4280	5920	1070	1200	880	1590	360	700
Gumbo limbo	0.31	0.32	3,300	4,800	740	0.85	3.0	3.2	1720	3080	560	370	270	800	200	360

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

TABLE 2. STATIC STRENGTH PROPERTIES OF AMERICAN WOODS AIR-DRIED TO 12 PERCENT MOISTURE CONTENT*—*Continued*

Species	Specific Gravity, Oven Dry Weight		Static Bending						Compression Parallel to Grain, psi		Compression Perpendicular to Grain, psi	Hardness, lb.		Shear, psi	Cleavage, lb./in. of Width	Tension Perpendicular to Grain, psi
			Stress at Proportional Limit, psi	Modulus of		Work, in.-lb./in.^{3}										
	Vol. at Test	Vol. Oven Dry		Rupture, psi	Elasticity, 1000 psi	Proportional Limit	Maximum Load	Total	Stress at Proportional Limit	Maximum Crushing Strength		End	Side			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hardwoods																
Hackberry	0.53	0.56	5,900	11,000	1190	1.72	12.8	27.3	3710	5,440	1100	1110	880	1590	330	580
Haw, pear	0.68	..	7,500	14,600	1270	2.50	23.6	34.0	....	6,760	1580	1960	1550	....	..	..
Hickory, bigleaf shagbark	0.69	..	8,900	18,100	1890	2.29	23.6	68.0	....	8,000	2220	....	....	2110	..	..
Hickory, bitternut	0.66	..	9,300	17,100	1790	2.73	18.2	68.7	....	9,040	2070	....	....	....	..	..
Hickory, mockernut	0.72	..	11,900	19,200	2220	3.41	22.6	67.5	....	8,940	2140	....	....	1740	..	..
Hickory, nutmeg	0.60	..	8,100	16,600	1700	2.04	25.1	..	....	6,910	1930	....	....	....	..	..
Hickory, pignut	0.75	..	11,300	20,100	2260	3.23	30.4	83.1	....	9,190	2450	....	....	2150	..	..
Hickory, shagbark	0.72	..	10,700	20,200	2160	3.01	25.8	78.2	....	9,210	2170	....	....	2430	..	..
Hickory, water	0.62	..	10,200	17,800	2020	2.88	19.3	42.3	5400	8,600	1910	....	....	....	..	..
Holly	0.57	0.61	6,100	10,300	1110	1.88	10.7	13.8	3380	5,540	1130	1400	1020	1710	..	680
Honeylocust	..	0.67	8,800	14,700	1630	2.74	13.3	42.3	5250	7,500	2280	1860	1580	2250	430	900
Hophornbeam	0.70	0.76	9,300	14,100	1700	2.96	14.0	31.3	5780	7,760	1500	2200	1860	1790	..	..
Inkwood	0.80	0.92	8,900	14,900	1910	2.34	10.3	22.4	4520	8,430	2530	3120	2220	2260	..	..
Ironwood, black (Leadwood)	1.15	1.08	7,200	18,200	2980	1.02	6.8	15.7	3400	9,940	2860	....	....	....	..	..
Laurel, California	0.55	0.59	5,400	8,000	940	1.85	8.2	12.8	3520	5,640	1400	1540	1270	1860	420	870
Laurel, mountain	0.68	0.74	8,600	11,100	1200	3.44	10.3	18.3	....	5,920	1820	2090	1790	....	..	..
Locust, black	0.69	0.71	12,800	19,400	2050	4.62	18.4	49.4	6800	10,180	2260	1580	1700	2480	330	640

Madrono, Pacific	0.65	0.69	7,300	10,400	1230	2.46	8.8	12.4	4040	6,880	1620	1890	1460	1810	490	..
Magnolia, cucumber	0.48	0.52	8,000	12,300	1820	1.98	12.2	22.4	4840	6,310	710	950	700	1340	290	660
Magnolia, evergreen	0.50	0.53	6,800	11,200	1400	1.90	12.8	16.8	3420	5,460	1060	1280	1020	1530	430	740
Magnolia, mountain	0.44	0.48	6,800	10,100	1400	1.86	10.0	15.8	4180	5,360	620	830	620	1150	320	660
Mangrove	0.96	1.06	14,000	21,700	2950	3.80	17.9	93.2	6170	10,750	3300	..	2760	2860	..	..
Maple, bigleaf	0.48	0.51	6,600	10,700	1450	1.66	7.8	11.8	4790	5,950	930	1330	850	1730	400	540
Maple, black	0.57	0.62	8,300	13,300	1620	2.39	12.5	21.5	4600	6,680	1250	1700	1180	1820	420	670
Maple, red	0.54	0.55	8,700	13,400	1640	2.84	12.5	27.4	4650	6,540	1240	1430	950	1850	500	..
Maple, silver	0.47	0.51	6,200	8,900	1140	1.90	8.3	13.1	4360	5,220	910	1140	700	1480	340	500
Maple, striped	0.46	..	5,200	10,900	1360	1.08	11.3	16.8	....	5,540	800	960	700	1320	..	..
Maple, sugar	0.63	0.68	9,500	15,800	1830	2.76	16.5	27.9	5390	7,830	1810	1840	1450	2330	..	..
Mastic	0.93	1.03	6,600	10,200	1780	1.39	6.2	6.6	3940	6,930	2830	2090	1790	1470	370	710
Oak, black	0.61	0.67	7,900	13,900	1640	2.15	13.7	24.0	4750	6,520	1150	1380	1210	1910	..	..
Oak, bur	0.64	0.67	6,400	10,300	1030	2.37	9.8	17.4	3580	6,060	1480	1410	1370	1820	320	680
Oak, California black	0.57	0.58	6,100	8,700	990	2.28	6.5	10.0	3300	5,640	1440	1180	1100	1470	360	770
Oak, canyon live	0.77	0.84	9,300	12,900	1610	3.15	9.9	21.5	6110	9,080	2260	2530	2420	2290	640	..
Oak, chestnut	0.66	0.67	9,000	13,300	1590	2.88	11.0	19.4	4420	6,830	1040	1250	1130	1490	380	..
Oak, laurel	0.63	0.70	7,700	12,600	1690	2.02	11.8	28.5	4640	6,980	1310	1230	1210	1830	360	790
Oak, live	0.89	0.98	8,700	18,400	1980	2.19	18.9	39.1	5120	8,900	3510	3150	2680	2660	520	1010
Oak, Oregon white	0.72	0.75	6,600	10,300	1100	2.28	9.8	18.2	3960	6,530	2110	1880	1660	2020	380	830
Oak, pin	0.63	0.68	8,000	14,000	1730	2.22	14.8	30.5	4620	6,820	1260	1600	1510	2080	530	1050
Oak, post	0.67	0.74	7,600	13,200	1510	2.25	13.2	40.4	3700	6,600	1760	1350	1360	1840	430	780
Oak, northern red	0.63	0.66	8,500	14,300	1820	2.33	14.5	33.4	4580	6,760	1250	1580	1290	1780	410	800
Oak, Rocky Mountain white (Oak, Gambel)	0.73	0.70	5,200	8,500	680	2.30	9.0	13.3	....	5,200	2070	2030	1440	....	..	..
Oak, scarlet	0.67	0.71	9,700	17,400	1910	2.92	20.5	43.9	5550	8,330	1380	1690	1400	1890	450	870
Oak, southern red	0.59	0.62	6,000	10,900	1490	1.44	9.4	15.9	2910	6,090	1080	1020	1060	1390	350	510
Oak, swamp red	0.68	0.71	11,200	18,100	2280	3.09	18.3	34.6	6350	8,740	1540	1570	1480	2000	410	840
Oak, swamp chestnut	0.67	0.76	7,300	13,900	1770	1.68	12.0	21.0	4400	7,270	1370	1290	1240	1990	350	690

---

[a] From **L. J. Markwardt and T. R. C. Wilson**, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

Table 2. Static Strength Properties of American Woods Air-Dried to 12 Percent Moisture Content*—*Continued*

Species	Specific Gravity, Oven Dry Weight		Static Bending						Compression Parallel to Grain, psi		Compression Perpendicular to Grain, psi	Hardness, lb.		Shear, psi	Cleavage, lb./in. of Width	Tension Perpendicular to Grain, psi
			Stress at Proportional Limit, psi	Modulus of		Work, in.-lb./in.^{3}										
	Vol. at Test	Vol. Oven Dry		Rupture, psi	Elasticity, 1000 psi	Proportional Limit	Maximum Load	Total	Stress at Proportional Limit	Maximum Crushing Strength		End	Side			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Oak, swamp white	0.72	0.79	10,200	17,700	2050	2.88	19.2	48.7	5830	8600	1470	1680	1620	2000	480	830
Oak, water	0.63	0.68	8,900	15,400	2020	2.24	21.5	33.4	3960	6770	1260	1400	1190	2020	470	920
Oak, white	0.68	0.71	8,200	15,200	1780	2.27	14.8	29.1	4760	7440	1320	1520	1360	2000	450	800
Oak, willow	0.69	0.69	9,300	14,500	1900	2.61	14.6	37.3	4380	7040	1400	1420	1460	1650	..	..
Osage-orange	..	0.84	....	....	..	..	..	..	....	....	..	..	..	..	..	..
Palmetto, cabbage	0.39	0.45	3,000	4,700	560	0.94	4.5	19.6	1450	2220	180	300	360	410	80	130
Paradise tree	0.34	0.36	3,900	5,300	850	0.88	3.1	4.0	2160	3000	400	600	350	620	..	330
Pecan	0.66	0.69	9,100	13,700	1730	2.81	13.8	35.5	5180	7850	2130	1930	1820	2080	660	..
Persimmon	0.74	0.78	10,900	17,700	2010	3.49	15.4	35.2	6390	9170	2460	2520	2300	2160	590	1200
Pigeon-plum	0.78	0.85	7,600	13,000	1290	2.67	10.8	..	4640	7020	2920	....	2030	..	..	..
Poisonwood	0.53	0.55	5,400	10,600	1290	1.25	6.4	6.5	....	4780	800	....	..	..	..	..
Poplar, balsam	0.33	0.35	4,200	6,800	1100	0.98	5.0	6.9	2920	4020	370	380	300	790	200	350
Poplar, yellow	0.40	0.43	6,100	9,200	1500	1.43	6.8	11.2	3550	5290	580	560	450	1100	280	520
Rhododendron, great	0.57	0.60	6,800	11,000	1110	2.30	12.4	23.0	....	6420	1440	..	..	..	..	..
Sassafras	0.45	0.47	6,200	9,000	1120	1.91	8.7	24.8	3260	4760	1050	650	630	1240	300	590
Serviceberry	0.74	0.79	11,000	16,900	1880	3.44	18.9	49.1	6340	8770	1790	2090	1800	1590	..	..
Silverbell	0.45	0.48	5,700	8,600	1320	1.46	6.9	18.0	3580	5130	680	880	590	1180	320	480
Sourwood	0.55	0.59	8,300	11,600	1540	2.44	10.9	21.7	4400	6190	1080	1350	940	1500	380	520
Stopper, red	0.87	0.92	....	16,200	2040	..	10.6	19.3	....	9790	2790	....	2600	1850	..	..

Sugarberry	0.51	0.54	6,200	9,900	1140	2.18	11.2	26.2	3970	5620	1240	1280	960	1280	380	..
Sumach, staghorn	0.47	..	7,800	10,200	1190	2.84	8.4	19.8	....	5940	1010	880	680	..	..	..
Sycamore	0.49	0.54	6,400	10,000	1420	1.66	8.5	14.3	3710	5380	860	920	770	1470	400	720
Walnut, black	0.55	0.56	10,500	14,600	1680	3.70	10.7	17.9	5780	7580	1250	1050	1010	1370	320	690
Walnut, little	0.57	0.61	8,300	14,200	1480	2.60	11.2	14.3	..	6760	..	..	..	..	..	..
Willow, black	0.37	0.41	3,900	6,200	720	1.94	7.9	11.1	2020	3420	480	550	450	1050	290	460
Willow, western black	0.44	0.47	5,500	8,500	1310	1.37	9.3	23.4	3120	4560	630	850	630	1160	290	530
Witch-hazel	0.61	0.71	9,100	15,200	1460	3.17	21.0	..	....	6740	1370	1860	1530	..	..	..
Softwoods																
Cedar, Alaska	0.44	0.46	7,100	11,100	1420	2.06	10.4	15.8	5210	6310	770	790	580	1130	180	360
Cedar, incense	0.37	0.37	5,900	8,000	1040	1.67	5.4	8.2	4760	5200	730	830	470	880	..	270
Cedar, Port Orford	0.42	0.44	7,700	11,300	1730	1.97	9.1	19.5	5890	6470	760	730	560	1080	220	400
Cedar, eastern red	0.47	0.49	3,800	8,800	880	1.01	8.3	..	....	6020	1140	900	900	..	260	..
Cedar, southern red	0.44	0.45	7,300	9,400	1170	1.88	5.4	6.6	5190	6570	1000	1010	610	750	..	..
Cedar, western red	0.33	0.34	5,300	7,700	1120	1.44	5.8	10.5	4360	5020	610	660	350	860	130	220
Cedar, northern white	0.31	0.32	4,900	6,500	800	1.72	4.8	6.0	2630	3960	380	450	320	850	150	240
Cedar, southern white (Cedar, Atlantic white)	0.32	0.35	4,800	6,800	930	1.46	4.1	5.2	2740	4700	500	520	350	800	130	220
Cypress, southern (Cypress, bald)	0.46	0.48	7,200	10,600	1440	2.15	8.2	11.9	4470	6360	900	660	510	1000	170	270
Douglas fir (coast type)	0.48	0.51	8,100	11,700	1920	1.96	8.6	22.9	6450	7420	910	760	670	1140	180	300
Douglas fir (intermediate type)	0.44	0.47	7,400	11,200	1640	1.87	8.8	16.4	5540	6720	920	710	600	1130	190	340
Douglas fir (Rocky Mt. type)	0.43	0.45	6,300	9,600	1400	1.60	6.4	11.3	4660	6060	820	740	630	1070	160	330
Fir, alpine	0.33	0.32	....	7,100	900	..	2.9	3.5	3740	4330	600	470	400	1020	140	..
Fir, balsam	0.36	0.41	5,200	7,600	1230	1.23	5.1	10.4	3970	4530	380	510	400	710	..	180
Fir, corkbark	0.30	0.32	4,500	6,900	1030	1.09	4.5	5.3	3820	4110	470	470	290	840	170	280

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U.S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

TABLE 2. STATIC STRENGTH PROPERTIES OF AMERICAN WOODS AIR-DRIED TO 12 PERCENT MOISTURE CONTENT*—*Continued*

Species	Specific Gravity, Oven Dry Weight		Static Bending						Compression Parallel to Grain, psi		Compression Perpendicular to Grain, psi	Hardness, lb.		Shear, psi	Cleavage, lb./in. of Width	Tension Perpendicular to Grain, psi
			Stress at Proportional Limit, psi	Modulus of		Work, in.-lb./in.^{3}										
	Vol. at Test	Vol. Oven Dry		Rupture, psi	Elasticity, 1000 psi	Proportional Limit	Maximum Load	Total	Stress at Proportional Limit	Maximum Crushing Strength		End	Side			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Fir, lowland white	0.40	0.42	5,800	9,300	1630	1.22	7.5	24.9	4420	5430	620	660	490	930	190	240
Fir, noble	0.38	0.40	6,600	10,100	1580	1.59	8.8	16.0	4960	5550	640	690	410	980	150	220
Fir, California red	0.39	0.42	7,200	11,200	1590	1.89	9.5	14.3	....	5290	850	1090	530	1050	190	350
Fir, silver	0.38	0.42	6,200	9,400	1530	1.40	9.3	21.6	4660	5550	490	620	430	1050	200	..
Fir, white	0.37	0.40	6,500	9,300	1380	1.72	6.7	11.4	3590	5350	600	730	440	930	160	260
Hemlock, eastern	0.40	0.43	6,100	8,900	1200	1.79	6.8	11.5	4020	5410	800	810	500	1060	150	..
Hemlock, mountain	0.47	0.51	7,400	11,200	1320	2.36	8.8	14.0	4620	6840	1030	1170	740	1230	170	320
Hemlock, western	0.42	0.44	6,800	10,100	1490	1.82	7.5	15.3	5340	6210	680	940	580	1170	200	310
Juniper, alligator	0.51	0.54	5,400	6,700	650	2.74	6.5	..	....	4120	1700	1290	1160	..	..	..
Larch, western	0.52	0.59	7,900	11,900	1710	2.46	8.0	18.5	5950	7490	1080	1110	760	1360	160	310
Pine, jack	0.43	0.46	5,000	7,900	1220	1.20	5.4	11.8	....	5400	820	660	580	1120	200	390
Pine, Jeffrey	0.40	0.42	7,200	9,300	1240	2.43	6.6	11.4	4240	5530	790	610	500	1210	250	380
Pine, limber	0.40	0.42	6,600	9,100	1170	2.13	6.8	8.7	....	5290	720	510	430	800	260	220
Pine, loblolly	0.51	0.54	7,800	12,800	1800	1.92	10.4	17.5	4820	7080	980	750	690	1370	270	470
Pine, lodgepole	0.41	0.43	6,700	9,400	1340	1.97	6.8	12.1	4310	5370	750	530	480	880	180	290
Pine, longleaf	0.58	0.62	9,300	14,700	1990	2.44	11.8	21.9	6150	8440	1190	920	870	1500	270	470
Pine, mountain	0.52	0.55	7,900	11,600	1550	2.30	8.7	15.8	4260	6830	1210	730	660	1200	200	360
Pine, northern white (Pine, eastern white)	0.36	0.37	6,000	8,800	1280	1.59	6.7	10.5	3680	4840	550	500	400	860	160	300

Pine, Norway (Pine, red)	0.48	0.51	9,400	12,500	1800	2.78	10.0	16.9	5330	7340	830	670	580	1230	200	490
Pine, pitch	0.49	0.52	6,900	10,800	1430	1.62	9.2	15.4	3960	5940	1010	700	620	1360	260	480
Pine, pond	0.54	0.58	8,300	11,600	1750	2.21	8.6	16.0	6300	7540	1120	780	740	1380	240	360
Pine, ponderosa	0.40	0.42	6,300	9,200	1260	1.85	6.6	10.8	4060	5270	740	550	450	1160	220	400
Pine, sand	0.48	0.51	6,700	11,600	1410	1.83	9.6	17.4	3900	6920	1030	950	730	1100	. .	300
Pine, shortleaf	0.51	0.54	7,700	12,800	1760	1.93	11.0	16.6	5090	7070	1000	750	690	1310	270	470
Pine, slash	0.61	0.66	9,800	15,900	2060	2.76	12.6	20.8	6280	9100	1390	1080	1010	1730	290	570
Pine, sugar	0.36	0.38	5,700	8,000	1200	1.53	5.5	8.0	4140	4770	590	530	380	1050	190	350
Pine, western white	0.38	0.42	6,200	9,500	1510	1.47	8.8	14.1	4480	5620	540	440	370	850	160	. .
Pinyon	0.53	0.57	5,600	7,800	1140	1.86	4.7	6.1	. . . .	6400	1520	920	860	. .	. .	. .
Redwood (virgin)	0.40	0.42	6,900	10,000	1340	2.04	6.9	8.8	4560	6150	860	790	480	940	150	240
Redwood (second growth, openly grown)	0.30	0.31	4,200	6,400	760	1.35	4.7	4.9	2660	3810	550	590	340	860	160	240
Redwood (second growth, closely grown)	0.34	0.36	5,500	8,300	1120	1.50	5.7	7.9	3750	5240	640	710	400	930	160	280
Spruce, black	0.40	0.43	5,800	10,300	1530	1.34	10.5	21.4	4520	5320	650	700	520	1030	160	. .
Spruce, Engelmann	0.33	0.35	6,000	8,500	1160	1.64	5.6	7.6	3580	4580	640	450	310	1010	200	. .
Spruce, red	0.41	0.41	6,800	10,200	1520	1.73	8.4	12.4	4610	5890	580	640	490	1080	180	350
Spruce, Sitka	0.40	0.42	6,700	10,200	1570	1.62	9.4	17.2	4780	5610	710	760	510	1150	210	370
Spruce, white	0.40	0.45	6,500	9,800	1340	1.76	7.7	14.8	3700	5470	570	610	480	1080	200	360
Tamarack	0.53	0.56	8,000	11,600	1640	2.19	7.1	15.1	4780	7160	990	670	590	1280	230	400
Yew, Pacific	0.62	0.67	9,300	15,200	1350	3.59	18.7	31.1	4730	8100	2110	2020	1600	2230	200	. .

From L. J. Markwardt and T. R. C Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

of wood. The values for modulus of rupture, derived from static-bending tests, shown in Tables 1 and 2 (col. 5) measure the approximate maximum tensile stress at the convex surface of beams tested in the green and air-dry conditions, and are commonly used as a conservative expression of tensile strength parallel to the grain.

Failure of wood in tension parallel to the grain practically always occurs in dry wood when subjected to flexure or bending, except perhaps in pieces that are so deep for their thickness that buckling occurs and in pieces that are so short in relation to depth that horizontal shear occurs (see Fig. 15*f*). The tension portion of the fracture is nearly the same as though the piece were pulled in two lengthwise. The fiber walls are torn across obliquely and usually in a spiral direction. There is practically no pulling apart of the fibers from each other, that is, no separation of the fibers along their walls, regardless of their thickness. The nature of tension failure is apparently not affected by the moisture condition of the specimen, at least not so much so as the other strength values.[5]

Tension perpendicular to the grain is closely related to cleavage resistance. The strength of a specimen of wood in this respect is determined by measuring the force (acting perpendicular to the grain) required to produce failure (see Fig. 84 and page 317). This maximum load (pounds) divided by the minimum area over which it is distributed (surface of failure, square inches) gives the tensile strength (pounds per square inch). Tables 1 and 2 (col. 17) show the average strength in tension perpendicular to the grain for a large number of American woods in the green and air-dry conditions. The strength values determined in this way are of use in estimating the resistance of timber to the splitting action of bolts and other fastenings.

The direction of the surface of failure with respect to the growth rings may have more or less influence on the strength of wood in tension perpendicular to the grain. In most woods the strength is greater when the surface of failure is tangential (parallel to the growth rings) than when it is radial (at right angles to rings), but notable exceptions are found, especially in air-dry material and wood characterized by interlocked grain.

---

[5] Warren D. Brush. A microscopic study of the mechanical failure of wood, *Rev. For. Serv. Investigations,* Washington, Vol. 2, 1913, p. 35.

When wood fails in this form of tension the thin fiber walls are torn in two lengthwise whereas the thick-walled fibers are usually pulled apart along the primary wall.

COMPRESSIVE OR CRUSHING STRENGTH

Compression perpendicular to the grain, or *sidewise compression,* is very closely related to hardness and transverse shear. There are two ways in which wood is subjected to stress of this kind, namely: (1) with a load acting over the entire upper area of the specimen, and (2) with a load concentrated over a portion of the area. The latter is the condition more commonly met in practice, as, for example, where a post rests on a horizontal sill, or a rail rests on a cross tie, and is used in making tests in compression across the grain (see Fig. 78). The former condition, however, gives the true resistance of the wood to simple crushing.

The first effect of compression perpendicular to the grain is to compact the fibers, the load gradually increasing as the density of the material is increased. If the specimen lies on a flat surface and the load is applied to only a portion of the upper area, the bearing plate indents the wood, crushing the upper fibers without affecting the lower part. As the load increases, the projecting ends sometimes split horizontally. The projection of the ends increases the strength of the material directly beneath the compressing weight by introducing a beam action which helps support the load. However, this influence is exerted for a short distance only.

In tests on this type of compression, the only strength values determined are those for *fiber stress at proportional limit,* which represents the greatest stress that the material will take without acquiring a permanent set (for method of determination see pages 309–12). The results of such tests on American woods in the green and air-dry conditions are indicated in Tables 1 and 2 (col. 12). These values are used in calculating bearing areas for beams, joists, and the like, and also serve to indicate the relative utility of different species for railroad ties, rollers, etc.

Compression parallel to the grain, *or endwise compression,* is involved in many uses of wood, such as columns, props, and posts, in which it is subjected to loads that tend to crush or shorten it lengthwise. However, in the long columns, that is, pieces in which the length is great compared with their least cross-sectional dimension, bending is introduced before the full crushing or compressive strength is reached, and the failure is by sidewise bending or flexure, instead of by crushing or splitting. In such columns the critical load is known as the Euler load, any load in excess of which will cause failure by bending. However, if a lateral deflection is given a long column or if sufficient crook is present, it may be made to deflect under an end load less than its critical Euler load. Removal of this load will permit the long column to resume its unbent position. A familiar instance of this action is afforded by a flexible walking stick.

The lateral bending of a long column carrying its full Euler load, and hence near failure, produces a combination of bending with compressive stress over the section, the compressive stress being maximum at the section of greatest deflection on the concave side. The convex surface is under tension, as in an ordinary beam test (see Fig. 3). If the same stick is braced in such a way that flexure is prevented, its supporting strength is increased enormously, since the compressive stress then acts uniformly over the section, and failure is by crushing or splitting, as in small blocks. In a column free to bend in any direction the deflection will be seen in the direction in which the column is least stiff. This sidewise bending can be overcome in studding, props, and compression members of trusses by bracing. The strength of a column also depends to some extent on whether the ends are free to turn or are fixed.

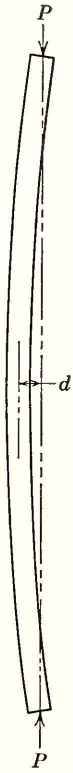


FIG. 3. Unequal distribution of stress in a long column due to lateral bending.

In determining the strength of wood for columns and similar uses, the complexity of the computations depends primarily on the ratio of the unsupported length of the member in question to its least cross-sectional dimension. Short columns, with unsupported length less than eleven times the least dimension, have practically the full compressive strength of the material, whereas in extremely long columns the strength is governed entirely by the stiffness of the wood, and its resistance to endwise compression is not involved. For material intermediate between these two extremes both the compressive strength and the stiffness of the wood are taken into consideration. The formulas used in calculating the strength of intermediate and long columns are discussed under Columns (pages 268–73).

Laboratory tests in compression parallel to the grain are made on short blocks or columns, of the form indicated in Figs. 74 and 75 (see pages 304–9 for method of conducting tests and formulas used in computing results). The values commonly obtained are the *maximum crushing strength, fiber stress at proportional limit,* and *modulus of elasticity.* A typical load–deformation curve obtained in such tests is shown in Fig. 76. Values of fiber stress at proportional limit and maximum crushing strength in compression parallel to grain for a large number of woods are shown in Tables 1 and 2 (cols. 10 and 11, respectively). Maximum crushing strength is a measure of the ability of a short column to withstand a slowly applied load and is derived by dividing the maximum load obtained in the test by the cross-sectional area over which that load was distributed. It is extensively used in calculating sizes of columns and other similarly loaded structural timbers, as well as in deriving safe working stresses for material of this class. Fiber stress at proportional limit, or the maximum stress that the material will take without injury, is seldom used in practice, preference being given to maximum crushing strength which is less variable and easier to obtain. The relationship between these two strength properties of wood is fairly constant, fiber stress at proportional limit averaging about 75 percent of maximum crushing strength for hardwoods and about 80 percent for softwoods. Modulus of elasticity is a measure of the stiffness of the wood. It is used in computing the strength of intermediate and long columns.

The compressive strength of wood parallel to the grain is about 3 to 10 times greater than that at right angles to the grain in the common American woods (see values for fiber stress at proportional limit, Tables 1 and 2, cols. 10 and 12). The ratio is about the same for both unseasoned and air-dry material.

Since tests in endwise compression to determine maximum crushing strength are simpler, easier to make, and less expensive than several other types of tests, they are frequently the only ones made in studying the effect of various conditions and treatments on the strength of wood. These tests are not necessarily representative of the other strength properties, however, and may occasionally lead to erroneous conclusions. For example, it was found that a certain heat treatment increased the crushing strength of some timbers 10 percent, while their resistance to impact was decreased 50 percent.[6]

When a short column is compressed along the grain until it breaks, the failure takes place in several progressive stages. The first indication of injury is the formation in the cell walls of fine crack-like lines, which Robinson[7] has termed *slip planes* or *slip lines*. These slip planes, which are found to be much more numerous in parts of cell walls that have actually failed in compression than in other parts, are not considered as definite regions of failure, however, since they are of too common occurrence in woods not subjected to test; in such cases they are probably due to compressive stresses resulting from the weight of the tree, wind action, felling or rough handling, or uneven longitudinal shrinkage. As the compression of the wood is continued, the slip planes become connected in more or less definite microscopic lines or zones, extending either horizontally or in an inclined direction across the growth rings (more often the latter, especially in summerwood). These localized injuries are recognized as the first definite indications of failure and are termed the *initial failures*[8,9] (see discussion of Compression Failures as defects, page 120).

Following the formation of the initial failures, the fibers (tracheids in conifers) adjacent to the points of rupture, which act as hollow tubes bound closely together, either (1) *buckle* or (2) *crinkle,* producing gross failures distinct to the unaided eye. In the first case the fibers are bent in such a way "that the parts originally in one axial line are no longer in that position, but, while remaining parallel to one another, have become displaced by a certain (perhaps small) distance, the actual 'buckle' forming the connection between the two parts. Crinkling results in a permanent deformation (telescoping) in the part that crinkles, but the parts of the fibers above and below remain in the same line or almost so."[10]

---

[6] J. A. Newlin and T. R. C. Wilson, *Mechanical properties of woods grown in the United States,* U. S. Dept. Agr. Bul. 556, Washington, 1917, p. 16.

[7] W. Robinson, The microscopical features of mechanical strains in timber and the bearing of these on the structure of the cell wall in plants, *Phil. Trans. Roy. Soc.*, London, Vol. 210, 1920.

[8] J. L. Bienfait, Relation of the manner of failure to the structure of wood under compression parallel to the grain, *Jour. Agr. Res.*, Washington, Vol. 33, July 15, 1926, pp. 185–7.

[9] The pits in the walls of the fibers or tracheids were assumed by Jaccard (P. Jaccard, Étude anatomique des bois comprimés, Mit. d. Schw. Centralanstalt f. d. Forst. Versuchswesen, Zurich, X Band, 1 Heft, 1910) to form the places of least resistance in the cell walls and to be the points at which the failures begin, but Bienfait (footnote 8) found no evidence to

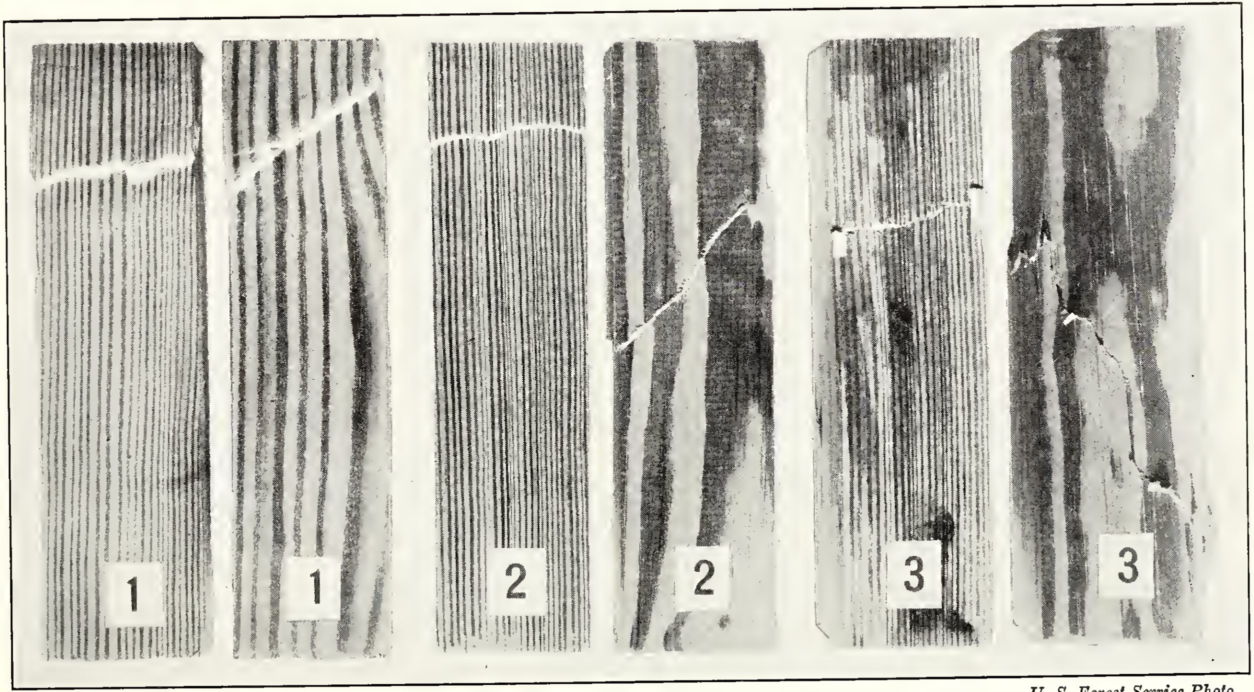
Crinkling is typical of dry, thin-walled cells and commonly characterizes the gross failure of seasoned white pine, spruce, and balsa wood. It is also noted in the early stages of gross failure in the springwood (early wood) of those woods, such as the hard pines, Douglas fir, and the ring-porous hardwoods, which exhibit a decided contrast in density between the two portions of the growth ring; in the final stages of failure, however, the springwood buckles to adapt itself to the contour of the general failure.

Buckling, on the other hand, is characteristic of thick-walled cells, such as make up the bulk of the dense summerwood (late wood) of southern pine, larch, hickory, oak, and numerous other woods (see Fig. 4). In such woods it is the summerwood that carries most of the compressive load. In species in which the fiber walls show all gradations of thickness—in other words, where the transition from the thin-walled cells of the early wood to the thick-walled cells of the late wood is gradual, or where the thick-walled elements are disposed more or less uniformly throughout the growth ring (as in maple, beech, gum, and similar diffuse-porous hardwoods)—the load is more evenly distributed over the cross section and the two kinds of failure, namely, buckling and crinkling, grade into each other. In some cases longitudinal splits occur which isolate bundles of elements by greater or less intervals.

---

support this contention. Another theory holds that the planes of contact of rays and fibers form points of weakness at which failures start, but examination reveals that any separation at these points takes place only after the buckling of the fibers has well started.

[10] Bienfait, footnote 8, p. 188. These terms are used in the same sense by Robinson, (*op. cit*), and are respectively synonymous to the terms "bending" and "buckling" used by Brush, footnote 5.



U. S. Forest Service Photo

FIG. 4. Endwise-compression failures in short southern pine columns of different degrees of dryness. 1. Unseasoned. 2. Air-dry. 3. Oven-dry. The right-hand member of each pair of specimens shows the inclination of failure on the tangential surface; the left-hand member shows the radial view of failure.

Moisture in wood decreases the stiffness of the fiber walls and enlarges the region of failure. The curve which the fiber walls make in the region of failure is more gradual and also more irregular in wet wood than in dry. In very dry wood, failure often occurs by splitting before any noticeable buckling takes place. Such splitting occurs by a tearing of the fibers or rays and not by separation of the rays from the adjacent elements (see Fig. 4).

Examination of test specimens which have failed in endwise compression will probably reveal considerable variation in the appearance of the gross failures. In timber testing, compression failures are classified as follows:

1. **Crushing,** in which the plane of rupture is approximately horizontal (Fig. 15*g*). This type of failure frequently occurs when the ends of test specimens are relatively wet.
2. **Wedge split,** in which shearing and splitting failures are combined (Fig. 15*h*).
3. **Shearing,** in which the plane of rupture makes an acute angle with the axis of the specimen (Figs. 4 and 15*i*). This is the normal type of failure and the one most often encountered.[11] It is discussed in detail in the following paragraphs.
4. **Splitting,** in which failure is characterized by a tearing of the fibers along a vertical plane (Fig. 15*j*). This form occasionally occurs in very dry specimens.
5. **Compression and shearing parallel to grain,** a form that usually occurs in cross-grained material (Fig. 15*k*). The test results obtained with specimens showing this type of failure should be discarded.

In the typical *shearing* type of failure the line of rupture is normally more or less inclined on the tangential (flat-sawn) surfaces, but at practically right angles to the grain on the radial

---

[11] "That the plane of failure would be inclined in one direction or another might be expected, since experiments show that materials which, like wood, are neither fully plastic nor easily pulverizable fail along inclined planes when subjected to compression, the angle of rupture being such as to cause failure under the least load necessary to effect a change. . . . (In wood) it is obvious that the least amount of friction and shearing will take place between fibers in buckling when their curvatures fit together most closely, a condition which can occur only when the curvature of one fiber is a little below that of the adjacent one. Hence the zone of a series of such curvatures would assume an angle with the horizontal." Bienfait, footnote 8, pp. 183, 189.

(quarter-sawn) faces (see Fig. 4). The line of rupture is occasionally inclined on radial faces, but in such cases it seldom forms a pronounced angle with the horizontal. Bienfait found that the general angle which the failure makes with the vertical on strictly tangential faces showed the following average values in the several species studied:

	Degrees
Sitka spruce (air-dry)	70
Douglas fir (air-dry)	64½
Douglas fir (moist)	63
Southern yellow pine (air-dry)	59½
White oak group (air-dry)	57

Various explanations have been advanced to explain the normal inclination of failure on the tangential faces of compression specimens. Thil[12] contended that the angle is determined by a supposed spiral arrangement of the rays as viewed on tangential section, the spirals acting as lines of least resistance. However, examination of test specimens shows no such relation; further, tests made at the Forest Products Laboratory on specimens of mahogany, in which the rays were disposed in horizontal rows, produced the same inclination of failure that typifies the other woods. It is sometimes considered that pronounced structural differences between springwood and summerwood, such as are to be found in Douglas fir, southern pine, oak, and hickory, are instrumental in producing the phenomenon. Little weight can be given to this theory, however, since woods in which no pronounced contrast exists between the two portions of the growth ring, such as white pine, spruce, maple, and birch, act in exactly the same manner as those first mentioned. The most satisfactory explanation of the phenomenon has been advanced by Bienfait, who concluded that it is caused by the stiffening effect of the rays, which increase the resistance to buckling in the direction of their length (radially), thus causing the inclination of the failure on the tangential face.

[12] A. Thil, Constitution anatomique du bois—étude sur les fractures des bois dans les essais de résistance, *Publié par commission des méthodes d'essai des matérioux de construction sous les auspices du Ministère des travaux publics de France,* Paris, Tome III, pp. 140–1, 1900.

SHEARING STRENGTH

Shearing strength is a measure of the ability of wood to resist forces that tend to cause one part of the material to slide or slip on another part adjacent to it. Shearing stresses are set up to a greater or less degree in most uses of wood, and the forces that produce them are classified, according to the direction in which they act, as (1) **shear parallel to** (along) **the grain,** (2) **shear perpendicular to** (across) **the grain,** and (3) **oblique shear.**

In Fig. 5, the action of the wood strut tends to shear off along the grain the portion *AB* of the wood tie rod, and it is essential that the length of this portion be great enough to guard against it. Figure 6 shows characteristic failures in shear parallel to the grain. The use of wood for pins or treenails involves resistance to shear across the grain. Another common instance of the latter is where the steel edge of the eye of an axe or hammer tends to cut off the handle. However, direct failure in shear across the grain in the plane of the cross section does not occur in wood, since the other properties are such that failure occurs in some other way, as by crushing across the grain or shear along the grain. Rolling shear, that is, the action resulting from application of a transverse load tending to cause the fibers to roll across one another in a longitudinal shear plane, is an entirely different and seldom encountered type of shear across the grain. The resistance of wood to rolling shear is somewhat less than to shear along the grain. The effect of oblique shear is commonly observed in the inclined plane of failure in short columns tested in compression parallel to the grain (see Fig. 4).

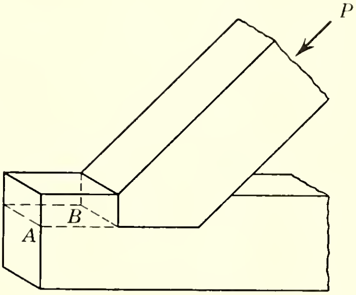


FIG. 5. Example of shear parallel to the grain.

Under certain conditions shearing stresses may act both perpendicular to the grain and parallel to it at the same time. Thus in a loaded beam the imposed weight tends to shear the wood across the grain. This stress is equal to the resultant force acting perpendicular to the axis of the beam at any point and varies in intensity in the different sections of the piece, according to the form of the beam and the method of loading. In a member uniformly loaded and supported at both ends the stress is maximum at the points of support and zero at the center (Fig. 11). In addition to the aforementioned stress there is a shearing force tending to move the fibers of the beam past each other in a longitudinal direction. In a beam this force is known as **horizontal shear.** The presence of this shear in the direction of the grain may be readily demonstrated by placing several boards one on top of the other and loading them at the center as indicated in Fig. 7. As the several boards bend, they slip over one another, so that the ends of each project beyond those of the one below it. In a solid beam this movement is restrained, and the longitudinal shear stresses developed are maximum at the neutral plane and decrease toward the upper and lower surfaces. In large members, however, failure by horizontal shear may occur considerably above or below the neutral plane, owing to the presence of checks or shakes (see Fig. 16).

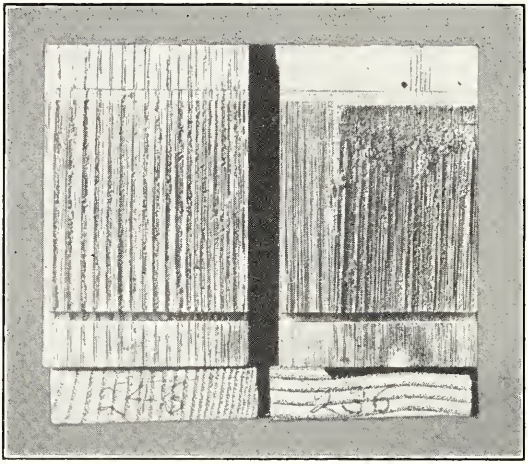


Fig. 6. Failure of test specimens in shear parallel to the grain. In the block at the left, the surface of failure is radial; in the one at the right, tangential.

The resistance of wood to shear perpendicular to the grain is so much greater than its ability to withstand shearing with the grain that the first-named form of stress is ignored in beams and similar members. On the other hand, bridge stringers and other forms of beams frequently fail under certain loading conditions owing to shear parallel to the grain, and such forces must be considered in designing forms of wood that may be subjected to bending in service. This latter type of shear is treated more in detail in the subsequent discussion of Failures in Beams (pages 48–52).

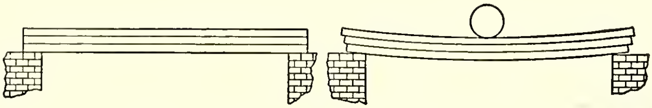


Fig. 7. Horizontal shear in a beam.

Shear perpendicular to the grain is so closely related to compression at right angles to the grain and to hardness that there is little to be gained by attempting to make separate tests on it. On the other hand, knowledge of shear parallel to the grain is important, since wood frequently fails in that way. The value of shearing stress parallel to the grain is determined from tests on small specimens of the form shown in Fig. 86. The maximum load in pounds (P) required to shear off the projecting lip of the specimen divided by the area of the shearing surface parallel to the direction of load in square inches (A) gives the unit values in pounds per square inch.

$$\left(\text{Shear} = \frac{P}{A}\right)$$

Tables 1 and 2 (col. 15) give the shearing strength parallel to the grain of American woods in the green and air-dry conditions.

The strength of small clear specimens in shear parallel to the grain is apparently not much affected by the direction of the surface of failure with respect to the growth rings, in either unseasoned or dry wood. On the other hand, in material containing such longitudinal separations as checks and shakes, which tend to reduce the area acting in resistance to shear, there may be a very marked effect. Checks, which normally extend along the rays, may greatly reduce the strength of wood when the surface of failure is radial; shakes, which commonly extend with the growth rings, affect the strength when the surface of failure is tangential. The nature of the shear failure in clear wood is largely dependent on the thickness of the cell walls, although it is affected to some extent by the moisture content of the wood; thick-walled fibers and unseasoned, thin-walled elements shows a characteristic tendency to separate from each other, while the thin-walled cells in seasoned wood are commonly torn in two lengthwise, the break usually following an individual fiber for the greater part of its length.[13]

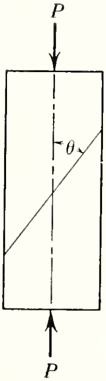


FIG. 8. Oblique shear in a short column.

Oblique shearing stresses are developed in a bar when it is subjected to direct tension or compression. If friction is neglected, the maximum shearing stress occurs along a plane when it makes an angle of 45 degrees with the axis of the specimen (see Fig. 8). In this case, shear $= P/2A$. When the value of the angle θ is other than 45 degrees, the shear[14] along the plane $= P/A \sin\theta \cos\theta$. Owing to the variability in the structure of wood, the plane of failure rarely coincides with the plane of maximum shearing stress (see page 34).

STRENGTH AS A BEAM[15]

When external forces acting in the same plane are applied at right angles to the axis of a simple beam so as to cause it to bend,

---

[13] Brush, footnote 5.

[14] This relationship is derived as follows:

P_s (the component of P acting in shear along the sloping plane) $= P \cos\theta$

A_s (the area resisting shear) bears the following relationship to the cross-sectional area (A):

$$A_s = \frac{A}{\sin\theta}$$

$$\text{Shearing stress} = \frac{P_s}{A_s} = \frac{P\cos\theta}{\dfrac{A}{\sin\theta}} = \frac{P}{A}\sin\theta\cos\theta$$

[15] There are three common forms of beams, namely:

(1) **Simple beam**—a bar resting on two supports, one near each end (Fig. 9).

(2) **Cantilever beam**—a bar resting on one support or fulcrum, or that

the three fundamental stresses—compression, tension, and shear—are set up within the piece, all acting in a direction parallel to the grain.[16] The compressive stresses cause a longitudinal shortening of the fibers on the concave side of the beam; the tensile stresses an elongation of the fibers on the convex side; and the horizontal shearing stresses a tendency toward longitudinal separation of the fibers by sliding of the upper part of the beam along the lower. Within the proportional limit the relative elongation (tension) and contraction (compression) of the fibers are directly[17] proportional to their distances from a plane intermediate between them—the **neutral plane** (N_1P in Fig. 10). The intersection of the neutral plane at any cross section is

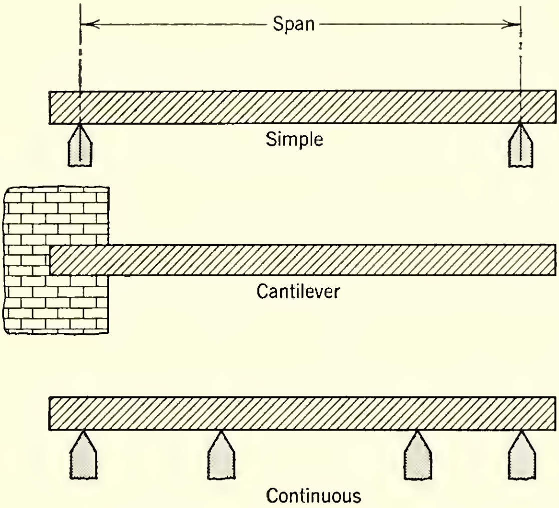


FIG. 9. Three common forms of beams.

---

portion of any beam projecting out of a wall or beyond a support (Fig. 9).

(3) **Continuous Beam**—a bar resting on more than two supports (Fig. 9).

The ensuing discussion pertains particularly to the first form, since it is the simplest, although it also applies, in general, to the other two forms.

[16] Compression and shearing stresses also act at right angles to the grain, but these are of minor importance, except that crushing failures may occur immediately under the load or above the supports when bearing areas are of insufficient size.

[17] While in reality this relationship does not exactly hold, the formulas for beams are based on its assumption.

known as the **neutral axis** of that section. Thus, the fibers halfway between the neutral axis and the outer surface experience only half as much shortening or elongation as the outermost or extreme fibers. Similarly for other distances. The elements along the neutral plane experience no tension or compression in the axial direction. Horizontal shear, on the other hand, is maximum at the neutral plane of a particular section and decreases to zero at the outermost elements of the section. The distribution of the three fundamental stresses in the direction of the depth of a simple beam is the same for all types of loading. The longitudinal distribution of the three stresses, on the other

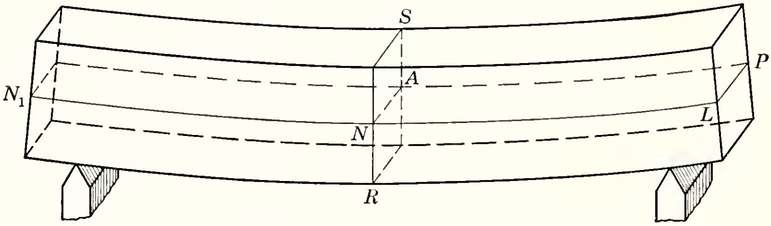


FIG. 10. Diagram of a simple beam. N_1P = neutral plane; NA = neutral axis of section RS.

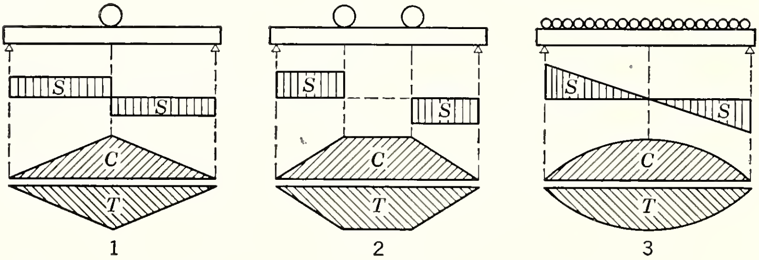


FIG. 11. Diagrams showing distribution of shear along neutral plane and of compression and tension on the upper and lower surfaces, respectively, from end to end of a simple beam under different types of loading. 1. Center loading. 2. Third-point loading. 3. Uniform loading. S = shear; C = compression; T = tension.

hand, shows considerable variation under the various forms of loading, as is indicated in Fig. 11.[18]

Stresses in Beams

An understanding of the stresses developed in a loaded beam requires some knowledge of elementary mechanics.[19] The tensile and compressive stresses developed at any point in a beam supporting a load may be calculated by the flexure formula commonly applied in engineering practice,

$$S = \frac{My}{I} \tag{1}$$

in which

S = stress in tension or compression, pounds per square inch
M = bending moment induced by the applied load, pound-inches
y = distance from neutral axis, inches
I = moment of inertia of the section, inches^4

The bending moment (M) at any section of a beam is a measure of the tendency of the forces acting on the beam to induce rotation about this point. When a beam is in a state of equilibrium, it is necessary to determine the moment resulting from the application of forces to one side only (customarily the left side) of the point for which the calculation is made.

Suppose, for example, that the bending moment were desired at the midpoint of a simple beam supported at the ends and carrying a concentrated center load as shown in Fig. 12. The two reactions at the supports must each be equal to one-half the total load (P), and the bending moment at midspan would

---

[18] "With uniform or rolling loads the tension and compression stresses in beams decrease from the center of the length of a beam towards the ends . . . The distribution is the same for both types of loading, although for the same load the stress resulting from the rolling load is twice that of the uniform load. The stresses developed by the third-point method of loading used in testing are constant over the center one-third of the length, and decrease from the center third toward the ends. . . . With the same intensity of stress at the center of the length, the uniform, rolling, and third-point loadings will give identical stresses at the quarter points. The maximum difference is at the third points, where the third-point loading gives 11 percent higher stresses. . . . The longitudinal distribution of the shear stresses is the same for rolling as for uniform loads, increasing in intensity toward the ends." J. A. Newlin and R. P. A. Johnson, Structural timbers—defects and their influence on strength, *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 24, Pt. 2, 1924, p. 982.

[19] Those desiring further information on this subject are referred to any textbook dealing with strength of materials.

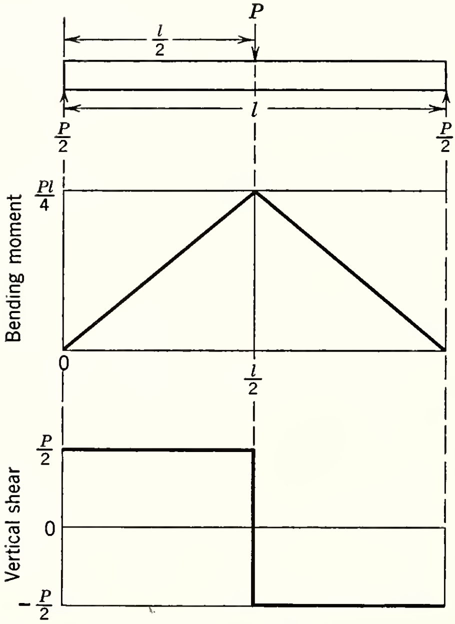


FIG. 12. Bending-moment and vertical-shear diagrams for a simple beam supported at the ends and carrying a concentrated load at midspan.

therefore be $Pl/4$, the product of the left reaction $P/2$ and the distance $l/2$ between the reaction and the midpoint of the beam. Similarly, the bending moment at a point one-fourth the length of the beam from its left end would be $P/2 \times l/4 = Pl/8$, and at a point three-fourths the length of the beam from the left end, $\frac{P}{2} \times \frac{3l}{4} - \left(P \times \frac{l}{4}\right) = \frac{3Pl}{8} - \frac{Pl}{4} = \frac{Pl}{8}$. Such a result might have been anticipated in view of the symmetry of the loading. It may be noted that moments acting to cause clockwise rotation about the point in question are considered as positive, and those tending to induce counterclockwise rotation are considered negative.

Uniformly distributed loads are treated as concentrated loads acting at their centers of gravity according to the procedure outlined as follows. For the beam shown in Fig. 13, carrying a distributed load (W), bending moment at midspan is calculated from $\frac{W}{2}\times\frac{l}{2}-\left(\frac{W}{2}\times\frac{l}{4}\right)=\frac{Wl}{4}-\frac{Wl}{8}=\frac{Wl}{8}$. (The negative moment in this calculation is the result of considering the load $(W/2)$ distributed over the left half of the beam as a concentrated load acting at its center of gravity with a moment arm of $l/4$.)

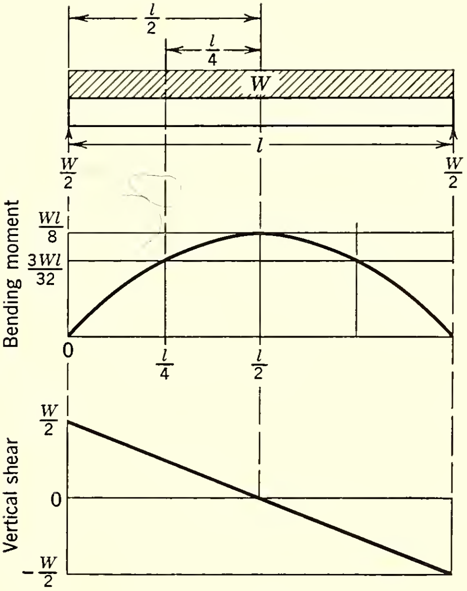


FIG. 13. Bending-moment and vertical-shear diagrams for a simple beam supported at the ends and carrying a uniformly distributed load.

It is evident that there can be no bending moment at the end of a freely supported beam in equilibrium since there is no opposing moment to resist any tendency toward rotation. Analysis of stresses in a beam that is not symmetrically loaded is dependent on this fact. Thus, for a beam loaded as in Fig. 14, the reaction R_1 at the left end support can be determined by considering the sum of the moments acting about the point of application of the reaction force R_2 as zero.

$$R_1l - \left(2P \times \frac{3l}{4}\right) - \frac{Pl}{2} = 0$$

$$R_1l = \frac{6Pl}{4} + \frac{Pl}{2} = \frac{8Pl}{4} = 2Pl$$

$$R_1 = 2P$$

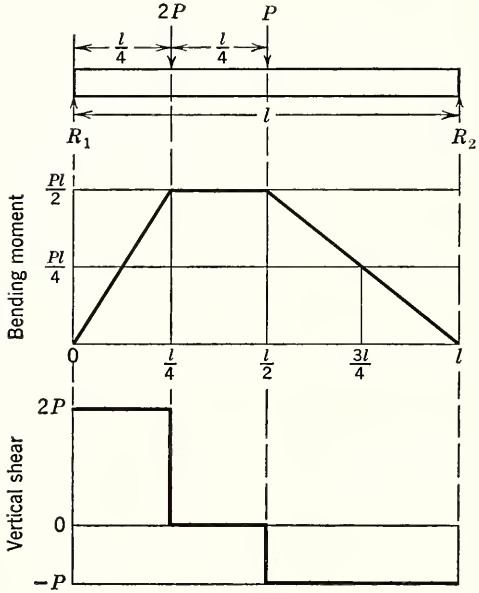


Fig. 14. Bending-moment and vertical-shear diagrams for a simple beam supported at the ends and carrying an unsymmetrical load.

Since the sum of the loads acting on a beam must be equal to the sum of the supporting reactions,

$$R_2 = 3P - 2P = P$$

Once the reaction forces R_1 and R_2 have been determined, calculation of the bending moment at any point along the length of the beam is readily carried out.

Plotted values of bending moment at various points along the span are used to construct moment diagrams such as those shown in Figs. 12, 13, and 14.[20]

Moment of inertia (I), appearing in the flexure formula, may be defined as a measure of the resistance which a cross section of a beam, because of the distribution of its area, offers to rotation about its neutral axis (Fig. 10). The moment of inertia is a property of the shape and dimensions of the cross section and, for a member of uniform composition is independent of the material composing the beam.

For any rectangular section loaded normally,

$$I = \frac{bd^3}{12} \tag{2}$$

in which

b = width, inches
d = depth, inches
I = moment of inertia, inches^4

The moment of inertia of a circular section is $I = \pi r^4/4$ in which r is the radius in inches.[21]

Compressive or tensile stress at any point in a beam may be determined by substituting appropriate values for M and y in the flexure formula (equation 1).

Suppose that the stress in tension 1 inch below the neutral plane at midspan in a beam, 2 by 4 inches in cross section and 36 inches long, loaded on its narrow face as shown in Fig. 12 is desired. Then,

$$M = \frac{Pl}{4} = \frac{36P}{4} = 9P$$

and

$$I = \frac{bd^3}{12} = \frac{2 \times 4^3}{12} = \frac{32}{3}$$

and

$$y = 1$$

---

[20] Moment diagrams for a large number of loading conditions are presented in *Wood structural design data,* Vol. I, Nat. Lbr. Mfrs. Assn., Washington, 1941, pp. 43–6.

[21] Moments of inertia for sections of other shapes may be found in any textbook on strength of materials.

Also see C. C. Forsaith, *Technology of New York state timbers,* N. Y. State Col. For. Tech. Publ. 18, Syracuse, 1926, pp. 150–3.

In this case,
$$S = \frac{9P \times 1}{\frac{32}{3}} = \frac{27P}{32}$$

and, if $P = 1000$ pounds, $S = 27{,}000/32 = 845$ pounds per square inch.

The maximum compressive or tensile stress in this beam would also occur at midspan, as shown by reference to the moment diagram (Fig. 12). Since maximum stress at any cross section occurs in the surface fiber (it is evident from the flexure formula that stress is directly proportional to y, distance from the neutral axis), the maximum value of y (one-half the depth of beam) is substituted in equation 1 when solving for maximum stress. The equation is expressed conventionally as

$$S = \frac{Mc}{I} \tag{3}$$

in which $c = \frac{1}{2}$ depth of beam.

In this case
$$S = \frac{9P \times 2}{\frac{32}{3}} = \frac{54P}{32}$$

and, if P is again 1000 pounds, $S = 54{,}000/32 = 1690$ pounds per square inch.

Horizontal and vertical shearing stresses are both developed in a beam as a result of the vertical forces exerted by the load and by the supports. The relative magnitude of these stresses at various points along the neutral plane of a simple beam is indicated in Fig. 11. Vertical shear at any section is merely the algebraic sum of the loads (taken as negative) and the reaction forces (taken as positive) acting to one side of the section. Plotted values for vertical shear at various points along the length of a beam constitute a vertical-shear diagram. Vertical shear is never directly responsible for the failure of wood beams, but its determination is necessary as a step in the calculation of horizontal shear.

Horizontal-shearing stress (H) may be calculated from the equation,

$$H = \frac{VQ}{It} \tag{4}$$

in which

V = vertical shear, pounds
Q = statical moment about the neutral axis of the area between the surface and the point at which shearing stress is to be determined, inches^3. (Statical moment is the product of the area as defined and the vertical distance from the center of gravity of this area to the neutral axis.)
I = moment of inertia of the section, inches^4
t = width of beam at the shearing plane, inches

A 2-by-4-inch beam, supported at the ends as in Fig. 12 and carrying a 1000-pound concentrated load at midspan, will develop a vertical shear amounting to 500 pounds (the reaction force) at the left support. As indicated in Fig. 12, this constant stress is maintained throughout the length of the beam. The change at midspan indicates merely a change in direction, not in magnitude, of vertical shear.

Substituting in equation 4 to calculate the horizontal-shearing stress at the end of the beam, 1 inch above or below the neutral plane, we have

$$H = \frac{500 \times (2 \times 1) \times 1\frac{1}{2}}{\frac{32}{3} \times 2}$$

$$= \frac{1500 \times 3}{64} = 70 \text{ pounds per square inch}$$

If the stress in beams of rectangular cross section is desired only at the neutral plane where, for any particular point along the length of the beam, shearing stress is maximum, equation 4 may be simplified to

$$H = \frac{3V}{2bd} \tag{5}$$

from which, in this case,

$$H = \frac{3 \times 500}{2 \times 2 \times 4} = 94 \text{ pounds per square inch}$$

It is evident from equation 4 that no horizontal-shearing stress exists at the upper or lower surfaces of the beam since the statical moment (Q) reduces to zero under these conditions.

In calculating vertical shear, it should be noted from Figs. 12 and 13 that a concentrated load, or portion of a distributed load located to the left of the point at which shearing stress is to be determined, is considered as negative (downward) and reaction forces to the left of the same point are considered as positive (upward) in obtaining the algebraic sum of vertical forces.

Failures in Beams

If a beam is loaded too heavily it will break or fail in some characteristic manner. These failures may be classified according to the way in which they develop, as compression, tension, and horizontal shear, and according to the appearance of the broken surface, as brash and fibrous. A number of forms may develop if the beam is completely ruptured.

Since the tensile strength of wood parallel to the grain is normally two to five times as great as the compressive strength in the same direction, a beam should, therefore, be expected to fail by the formation in the first place of a fold on the compression side due to the crushing action, followed by failure on the tension side. This is notably the case in unseasoned wood. In dry material the compression failure may be indistinct and the first visible failure may occur on the lower or tension side, a phenomenon that may be due in part to the fact that drying apparently increases the compressive strength of the wood to a greater extent than the tensile strength.[22]

[22] "The ratio of the strength in compression along the grain to the strength in tension along the grain has an important relation to the toughness of wood and its suitability for permanent bending. A piece in which the tensile strength is several times that of the compressive strength can be bent a great deal before it breaks, because of the buckling of the fibers which takes place on the compression side before failure occurs on the tension side. On the other hand, if the tensile strength is not much greater than the compressive strength, the stick will snap across on the tension side with comparatively little bending. In such a case the fracture occurs more or less abruptly across the grain, giving the wood the characteristic appearance of what is commonly known as *brash*.

"Moisture and heat decrease the strength in compression more than the strength in tension, and, hence, a steamed or boiled piece of wood can be bent more before it breaks on the convex side than can a cold dry piece."—A. Koehler, *The properties and uses of wood,* McGraw-Hill Book Co., New York, 1924, pp. 95–6.

Within the proportional limit it is assumed that the elongations and shortenings are equal and in a beam of symmetrical cross section that the neutral plane lies midway between the upper and lower surfaces (see Fig. 10). Later the top layer of fibers on the upper or compression side fails, and, as the load increases, the next layer of fibers fails, and so on, even though this failure may not be visible. As a result the shortening on the upper side of the beam becomes considerably greater than the elongation on the lower side. The neutral plane must be presumed to begin to sink gradually toward the tension side as soon as the proportional limit is passed, although its location at any time is very uncertain. This migration of the neutral plane increases the compression area and reduces the tension area. When the stresses in the outer fibers of the tension area become sufficiently great, the fibers are ruptured. The rupture is often irregular, as in direct tension tests. Failure may occur partially in single bundles of fibers some time before the final failure takes place.

There is considerable variation in tension failures, depending on the toughness or the brittleness of the wood, the arrangement of the grain, defects, and so on, thus making further classification desirable. The four most common forms are:

1. **Simple tension,** in which there is a direct pulling in two of the wood on the under side of the beam due to a tensile stress parallel to the grain (see Fig. 15*a*). This is common in straight-grained beams, particularly when the wood is seasoned.

2. **Cross-grained tension,** in which the fracture is caused by a tensile force acting obliquely to the grain (see Figs. 15*b*, and 25). This is a common form of failure where the beam has diagonal, spiral, or other form of cross grain on its lower side. Since the tensile strength of wood across the grain is only a small fraction of that with the grain, it is easy to see why a cross-grained timber would fail in this manner.

3. **Splintering tension,** in which the failure zigzags back and forth, producing a ragged or splintery break on the tension side of the beam (see Fig. 15*c*). This is common in tough woods. In this case the surface of fracture is fibrous.

4. **Brittle tension,** in which the beam fails by a clean break extending entirely through it (see Fig. 15*d*). It is characteristic of a brittle wood which gives way suddenly without warning, like

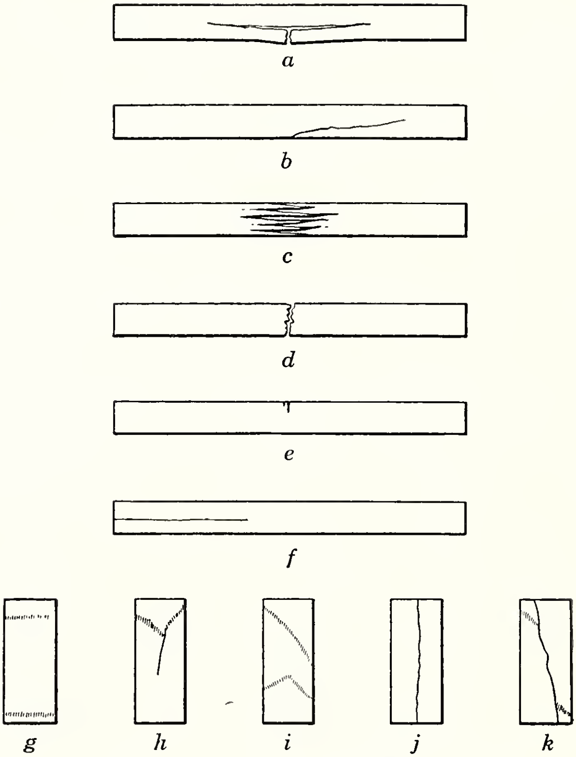


Fig. 15. Types of failure in simple beams subjected to bending (*a*–*f*) and in short columns subjected to compression parallel to the grain (*g*–*k*). See text for classification.

a piece of chalk. In this case the surface of fracture is described as *brash.*[23]

[23] Brashness or brittleness is evidently associated, at least in certain cases, with variations in the anatomy of the wood. Thus, specimens of low density for a given species, in which the percent of summerwood is small or the fibers are unusually thin walled, are likely to be brash. See C. C. Forsaith, The morphology of wood in relation to brashness, *Jour. For.,* Washington, Vol. 19, March 1921, pp. 237–49.

Frequently, however, the condition can be definitely attributed to the presence of compression wood, compression failures, or incipient decay, or to exposure of the material to extremely high temperatures. See text discussion of Temperature (pages 188–91), Decay (pages 117–19), and Compression Failures and Cross Breaks (pages 120–2). Also Arthur Koehler, *Causes of brashness in wood,* U. S. Dept. Agr. Tech. Bul. 342, Washington, 1933.

In addition to tension failures the following types may also occur:

Compression failure (Fig. 15*e*) has few variations except that it appears at various distances from the neutral plane of the beam. It is particularly conspicuous in unseasoned timbers. The compressive stress parallel to the fibers causes them to buckle or bend as in an endwise compression test. This action usually begins on the top side shortly after the elastic limit is reached and extends downward, sometimes passing the neutral plane before complete failure occurs. Frequently two or more failures develop at about the same time. In dense woods compression failures may take the form of diagonal shear (Fig. 15*i*) or wedge split (Fig. 15*h*).

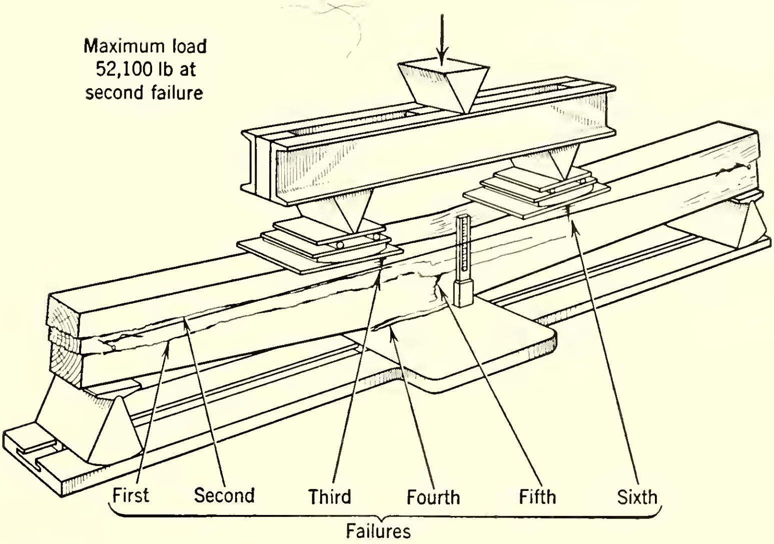


FIG. 16. Failure of a large beam by horizontal shear.

Horizontal-shear failure, in which the upper and lower portions of the beam slide along each other for a portion of their length at either one or both ends (Fig. 15*f*), is fairly common when the ratio of the height of the beam to the span is relatively large, since it is the short, deep beam that is often subjected to loads that develop the maximum shearing stress. It is not common in small clear specimens of the standard size used in tests. It is often due to shake or season checks, common in large timbers, which reduce the actual area resisting the shearing action considerably below the calculated area used in the formula for horizontal shear. For this reason it is unsafe, in designing large timber beams, to use shearing stresses higher than those calculated for beams that failed in horizontal shear. The effect of a failure in horizontal shear is to divide the beam into two or more beams, the combined strength of which is much less than that of the original beam. For this reason, a continuous load that is great enough to cause horizontal shear will probably also cause complete failure of the beam, unless shearing is induced by checks or shakes or the beam is very short and deep. Figure 16 shows a large beam in which two failures in horizontal shear occurred at the same end. That the parts behave independently is shown by the compression failure below the original location of the neutral plane.

Table 3 gives an analysis of the causes of first failure in 840 structural beams of nine different species of conifers. Of the total number tested 265 were air-dried, and the remainder were unseasoned. The failure occurring first signifies the point of greatest weakness in the specimen under the particular conditions of loading employed (in this case, third-point loading).

Kinds of Loads

The kinds of loads to which beams are subjected may be classified (1) according to their distribution, as uniform or concentrated loads, and (2) with regard to their permanence, as live or dead loads.

Uniform load occurs where the load is distributed evenly over the beam (see Fig. 11).

Concentrated load occurs where the load is applied at a single point or points. In testing small clear beams the load is concentrated at the center of the span; in material of structural sizes, containing defects, it is usually applied at two points one third of the span of the beam apart (see Figs. 11 and 16). This latter type of loading, which is known as **third-point loading,** is extremely important in studying the influence of defects on the strength of wood, since the resultant stresses are uniform throughout the center third of the beam.

Live or **immediate load** is one that is not fixed and may be removed from a structure at any time. Such a load may be im-

TABLE 3. MANNER OF FIRST FAILURE OF LARGE BEAMS

(From U. S. For. Serv. Bul. 108, p. 56)

Species	Total Number of Tests	Percent of Total Failing by		
		Tension	Compression	Shear
Longleaf pine				
green	17	18	24	58
dry	9	22	22	56
Douglas fir				
green	191	27	72	1
dry	91	19	76	5
Shortleaf pine				
green	48	27	56	17
dry	13	54	..	46
Western larch				
green	62	23	71	6
dry	52	54	19	27
Loblolly pine				
green	111	40	53	7
dry	25	60	12	28
Tamarack				
green	30	37	53	10
dry	9	45	22	33
Western hemlock				
green	39	21	74	5
dry	44	11	66	23
Redwood				
green	28	43	50	7
dry	12	83	17	..
Norway pine				
green	49	18	76	6
dry	10	30	60	10

These tests were made on beams ranging in cross section from 4″ × 10″ to 8″ × 16″, and with a span of 15 feet.

posed momentarily, or it may be of indeterminate or moderately long duration. The type of live load to which highway bridges and railroad stringers are commonly subjected is known as **rolling** or **moving load.**

Dead or **permanent load** is one that is fixed and constant and remains as long as the structure itself. In the case of a bridge the weight of the structure itself is the dead load. All large beams support a uniform dead load consisting of their own weight.

A momentary load two or more times as great as the dead load or long-continued live load may be supported by a wood beam. Loads greater than the proportional limit are unsafe and will generally result in failure if continued long enough. A beam may be considered safe under long-continued load when the increments of deflection diminish during equal successive periods of time. A continued increase in deflection indicates an unsafe load which is almost certain to rupture the beam eventually.

Variations in the humidity of the surrounding air influence the deflection of dry wood under dead load and long-continued live load, and increased deflections during damp weather are cumulative and not recovered by subsequent drying. Increased moisture content, due to greater humidity of the air, lowers the proportional limit of wood so that what was a safe load for the dry material may become unsafe.

When a long-continued live load not great enough to rupture a beam has been removed, the beam tends gradually to recover its former shape, but the recovery is not always complete. If specimens from such a beam are tested in the ordinary testing machine, it will be found that the application of the load of long duration did not affect the stiffness, ultimate strength, or proportional limit of the material. In other words, the deflections and recoveries produced by momentary loads are the same as would have been produced had not the beam previously been subjected to a load of long duration.[24]

Safe load is the load considered safe for a material to support in actual practice. It is always less than the load at proportional limit and is usually taken as a certain proportion of the ultimate or breaking load.

The ratio of the breaking load to the safe load is preferably termed the **reduction factor,** rather than **factor of safety,** a term sometimes used incorrectly. In order to make due allowance for the natural variations and imperfections in wood and for the effect of continued stress, as well as for variations in the load, applied in the aggregate structure, the reduction factor is often as high as 4 or 6, especially if the safety of human life depends on the structure. This means that only one fourth to one sixth of the average computed strength value is considered safe to use in structural timber. The significance and application of the reduction factor in computing safe working stresses are discussed under Working Stresses for Structural Lumber in Part 3.

---

[24] See Harry D. Tiemann, Some results of dead load bending tests of timber by means of a recording deflectometer, *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 9, 1909, pp. 534–48.

The term "dead load" as here used by Tiemann is considered, in this text, to be a "live load" of long duration.

Application of Loads

There are three[25] general methods by which loads may be applied to beams, namely:

1. **Static loading,** or the gradual imposition of load so that the moving parts acquire no appreciable momentum. Loads are so applied in the ordinary testing machine.

2. **Sudden imposition of load without initial velocity.** "Thus in the case of placing a load on a beam, if the load be brought into contact with the beam, but its weight sustained by external means, as by a cord, and then this external support be *suddenly* (instantaneously) removed, as by quickly cutting the cord, then, although the load is already touching the beam (and hence there is no real impact), yet the beam is at first offering no resistance, as it has as yet suffered no deformation. Furthermore, as the beam deflects the resistance increases, but does not come to be equal to the load until it has attained its normal deflection. In the meantime there has been an unbalanced force of gravity acting, of a constantly diminishing amount, equal at first to the entire load, but now reduced to zero when the resistance has come to be equal to the load, at the normal deflection. But at this instant both the load and the beam are in motion, the hitherto unbalanced force having produced an accelerated velocity, and this velocity of the weight and beam gives to them an energy, or *vis viva,* which must now spend itself in overcoming an *excess* of resistance over and above the imposed load, and the whole mass will not stop until the deflection (as well as the resistance) has come to be equal to *twice* that corresponding to the static load imposed. Hence we say the effect of a suddenly imposed load is to produce twice the deflection and stress of the same load statically placed. It must be evident, however, that this case has nothing in com-

---

[25] A fourth type of loading might be added, namely, **vibratory,** or **harmonic repetition,** which is frequently serious in the case of bridges.

mon with either the ordinary 'static' tests of structural materials in testing-machines, or with impact tests."[26]

3. **Impact, shock,** or **blow.**[27] There are various common uses of wood that subject the material to sudden shocks and jars, or impact. Such is the action on a drop-forge hammer board, on a hammer handle when a blow is struck, or on a maul when it strikes a wedge.

Resistance to impact is resistance to energy which is measured by the product of the force and the distance through which it moves, or by the product of one-half the moving mass which causes the shock and the square of its velocity. The work done on the piece at the instant the velocity is entirely removed from the striking body is equal to the total energy of that body. It is impossible, however, to store all the energy of the striking body in the specimen, though the greater the mass and the shorter the distance through which it moves, or, in other words, the greater the proportion of weight and the smaller the proportion of velocity making up the energy of the striking body, the more energy the specimen will absorb. The rest is lost in friction, vibration, heat, and motion of the anvil.

In impact the stresses produced become very complex and difficult to measure, especially if the velocity is high, or the mass of the beam itself is large compared to that of the moving weight.

The difficulties attending the measurement of the stresses beyond the proportional limit are so great that they are not commonly determined. Within the proportional limit the formulas for calculating the stresses are based on the assumption that the deflection is proportional to the stress in this case as in static tests.

The standard method of making tests on the resistance of wood to shock is to support a small beam at the ends and drop a heavy weight on it at midspan[28] (see Fig. 72). Results of standard impact tests on American woods are presented in Table 4. The height of the weight is increased after each drop, and records of the corresponding deflections are taken until failure. The total work done on the specimen is equal to the scaled area under the curve of the resultant stress–strain diagram plus the effect of local inertia of the molecules at point of contact. Values for fiber stress at proportional limit, as determined from impact tests on unseasoned wood, average more than twice as great as similar values from static-bending tests,[29] and about 30 percent greater than values for modulus of rupture. Elastic resilience averages more than three times as great as in static bending. (Compare values for work to proportional limit in impact, Table 4, with those in static bending, Tables 1 and 2.)

---

[26] J. B. Johnson, *The materials of construction,* John Wiley & Sons, New York, 1902, pp. 81–2.

[27] See Harry D. Tiemann, The theory of impact and its application to testing materials, *Jour. Franklin Inst.,* Philadelphia, Vol. 168, Oct., Nov. 1909, pp. 235–59, 336–64.

Also Armin Elmendorf, Stresses in impact, *Ibid.,* Vol. 182, Dec. 1916, pp. 771–90.

[28] For discussion of various forms of impact tests see T. R. C. Wilson, Impact tests of wood, *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 22, Pt. 2, 1922, pp. 55–70. Also L. J. Markwardt and T. R. C. Wilson, *Strength*

The stresses involved in impact are complicated by the fact that there are various ways in which the energy of the striking body may be spent:

1. It produces a local deformation of both bodies at the surface of contact, within or beyond the proportional limit. In testing wood the compression of the substance of the steel striking weight may be neglected, since the steel is very hard in comparison with the wood. In addition to the compression of the fibers at the surface of contact, resistance is also offered by the inertia of the particles there, the combined effect of which is a stress at the surface of contact often entirely out of proportion to the compression that would result from the action of a static force of the same magnitude. It frequently exceeds the crushing strength at the extreme surface of contact, as in the case of the swaging action of a hammer on the head of an iron spike, or of a locomotive wheel on the steel rail. This is also the case when a bullet is shot through a board or a pane of glass without breaking it as a whole.

2. It may move the struck body as a whole with an accelerated velocity, the resistance consisting of the inertia of the body. This effect is seen when a golf ball is struck with a club.

3. It may deform a fixed body against its external supports

---

and related properties of woods grown in the United States, U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935, p. 14.

[29] This serves to explain why a small beam, when suddenly loaded, bends about twice as far to the proportional limit as when loaded slowly.

TABLE 4. IMPACT-BENDING STRENGTH PROPERTIES OF AMERICAN WOODS*

Species	Stress at Proportional Limit, psi		Work to Proportional Limit, in.-lb./in.^{3}		Height of Drop Causing Complete Failure, in. (50-pound Hammer)	
	Green	Air-dry†	Green	Air-dry†	Green	Air-dry†
Hardwoods						
Alder, red	8,000	11,600	2.6	4.8	22	20
Apple	7,600	15,700	3.0	7.8	33	43
Ash, Biltmore	11,900	16,500	4.9	7.9	30	40
Ash, black	.....	.....	...	...	33	35
Ash, blue	11,100	18,400	5.0	9.2	43	42
Ash, green	11,400	16,400	5.0	7.6	35	32
Ash, Oregon	8,900	13,300	3.0	5.2	39	33
Ash, pumpkin	8,800	13,600	3.7	6.8	31	24
Ash, white	13,900	17,000	5.9	8.2	38	43
Aspen	7,000	9,000	2.7	3.4	22	21
Aspen, largetooth	7,400	11,400	2.5	4.7	18	22
Basswood	6,300	9,800	2.1	3.8	16	16
Beech	11,500	16,000	4.4	7.0	43	41
Beech, blue (Hornbeam, American)	10,100	10,300	4.0	4.3	106	..
Birch, Alaska white	9,800	13,700	3.7	4.8	37	40
Birch, gray	7,400	10,400	2.6	3.5	59	35
Birch, paper	8,000	12,400	2.7	4.8	49	34
Birch, sweet	10,500	24,800	3.2	10.6	48	47
Birch, yellow	11,500	17,200	4.4	7.3	48	55
Blackwood	15,900	.....	6.8	...	42	..
Buckeye, yellow	6,500	10,000	2.1	4.3	18	16
Bustic	.....	18,400	...	6.6	..	26
Butternut	7,300	11,200	2.5	4.6	24	24
Buttonwood	14,100	.....	6.8	...	40	..
Cascara	8,700	10,200	3.6	4.6	58	26
Catalpa, hardy	7,500	11,000	3.1	4.3	35	27
Cherry, black	10,200	13,600	4.1	5.4	33	29
Cherry, pin	6,600	10,100	2.1	4.0	22	31
Chestnut	7,900	10,700	2.8	4.6	24	19
Chinquapin, golden	8,800	10,900	3.4	4.8	31	30

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

† Air-dried to 12 percent moisture content.

TABLE 4. IMPACT-BENDING STRENGTH PROPERTIES OF AMERICAN WOODS*—*Continued*

Species	Stress at Proportional Limit, psi		Work to Proportional Limit, in.-lb./in.^{3}		Height of Drop Causing Complete Failure, in. (50-pound Hammer)	
	Green	Air-dry†	Green	Air-dry†	Green	Air-dry†
Hardwoods						
Cottonwood, eastern	7,200	7,300	2.3	2.4	21	20
Cottonwood, northern black	6,800	9,800	2.2	3.8	20	22
Dogwood	7,100	14,600	3.5	7.5	58	44
Dogwood, Pacific	9,800	10,500	3.6	3.7	56	34
Elder, blueberry	8,000	10,500	2.9	5.1	38	33
Elm, American (Elm, white)	.....	.....	...	...	38	39
Elm, rock	.....	.....	4.6	7.9	54	56
Elm, slippery	9,200	15,300	3.4	7.5	47	45
Fig, golden	.....	.....	...	...	..	..
Gum, black (Tupelo, black)	9,800	14,500	4.0	7.1	30	22
Gum, blue	14,200	20,500	4.7	8.8	40	41
Gum, red (Gum, sweet)	10,000	16,800	3.9	8.5	33	32
Gum, tupelo (Tupelo, water)	9,000	12,500	3.3	5.8	30	23
Gumbo limbo	5,000	6,300	2.3	2.3	13	9
Hackberry	7,900	13,700	3.1	7.0	48	43
Haw, pear	.....	.....	...	...	..	..
Hickory, bigleaf shagbark	14,200	22,800	7.0	13.9	104	88
Hickory, bitternut	15,900	23,600	8.5	12.5	66	66
Hickory, mockernut	15,100	20,200	6.7	9.7	88	77
Hickory, nutmeg	12,800	.....	6.1	...	54	..
Hickory, pignut	16,900	25,200	8.8	13.2	89	74
Hickory, shagbark	14,400	19,300	6.4	9.0	74	67
Hickory, water	13,700	.....	6.1	...	56	53
Holly	8,900	12,500	4.4	6.9	51	33
Honeylocust	11,800	15,400	4.6	7.4	47	47
Hophornbeam	10,600	14,200	3.5	5.8	73	49

---

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

† Air-dried to 12 percent moisture content.

Table 4. Impact-Bending Strength Properties of American Woods*—*Continued*

Species	Stress at Proportional Limit, psi		Work to Proportional Limit, in.-lb./in.^{3}		Height of Drop Causing Complete Failure, in. (50-pound Hammer)	
	Green	Air-dry†	Green	Air-dry†	Green	Air-dry†
Hardwoods						
Inkwood	15,200	.....	6.8	...	50	28
Ironwood, black (Leadwood)	18,500	16,500	7.7	5.2	35	14
Laurel, California	8,300	10,700	4.1	5.3	57	31
Laurel, mountain	10,200	14,300	5.2	7.5	32	40
Locust, black	18,300	21,100	7.9	9.8	44	57
Madrono, Pacific	10,200	10,400	4.7	4.3	40	23
Magnolia, cucumber	9,300	14,700	2.9	5.7	30	35
Magnolia, evergreen	8,800	13,600	3.2	6.4	54	29
Magnolia, mountain	8,600	13,800	2.9	5.8	23	27
Mangrove	20,500	.....	8.2	...	52	32
Maple, bigleaf	8,500	.....	2.8	...	23	28
Maple, black	10,200	13,500	3.8	5.6	48	40
Maple, red	.....	.....	...	...	32	32
Maple, silver	6,800	12,400	2.6	6.9	29	25
Maple, striped	8,700	11,400	2.3	5.2	36	27
Maple, sugar	12,200	20,600	4.8	9.3	40	39
Mastic	18,000	14,100	8.7	5.1	52	24
Oak, black	11,400	14,400	4.9	6.4	40	41
Oak, bur	10,000	14,600	4.7	8.0	44	29
Oak, California black	8,200	8,800	3.4	4.0	30	16
Oak, canyon live	11,200	13,000	3.9	5.5	47	37
Oak, chestnut	12,000	18,600	4.6	7.7	35	40
Oak, laurel	10,400	14,700	3.4	5.6	39	39
Oak, live	17,200	21,300	8.5	11.2	57	33
Oak, Oregon white	10,300	11,900	4.8	5.4	49	29
Oak, pin	11,900	12,300	4.2	3.6	48	45
Oak, post	10,900	17,600	4.1	8.6	44	46
Oak, northern red	10,600	17,600	3.8	8.5	44	43
Oak, Rocky Mountain white (Oak, Gambel)	8,100	14,100	4.3	5.2	80	23

---

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

† Air-dried to 12 percent moisture content.

Table 4. Impact-Bending Strength Properties of American Woods*—*Continued*

Species	Stress at Proportional Limit, psi		Work to Proportional Limit, in.-lb./in.^{3}		Height of Drop Causing Complete Failure, in. (50-pound Hammer)	
	Green	Air-dry†	Green	Air-dry†	Green	Air-dry†
Hardwoods						
Oak, scarlet	11,900	16,100	4.0	6.1	54	53
Oak, southern red	9,100	15,300	3.1	7.3	29	26
Oak, swamp red	12,300	23,900	3.8	12.0	54	49
Oak, swamp chestnut	10,400	19,000	3.2	7.9	45	41
Oak, swamp white	13,300	22,300	4.8	11.2	50	49
Oak, water	11,600	18,800	3.8	8.1	39	44
Oak, white	10,700	17,100	4.2	7.5	42	37
Oak, willow	9,200	15,600	2.9	7.6	35	42
Osage-orange	15,500	.....	8.9	...	120	..
Palmetto, cabbage	5,000	6,200	2.7	2.9	15	16
Paradise tree	5,400	5,500	1.9	1.5	7	7
Pecan	12,300	17,400	5.0	8.2	53	44
Persimmon	12,100	18,400	4.5	8.6	41	37
Pigeon-plum	16,000	.....	6.8	...	40	..
Poisonwood	8,100	.....	3.3	...	15	..
Poplar, balsam	6,000	8,000	2.2	2.7	16	14
Poplar, yellow	8,600	13,500	3.3	5.6	18	20
Rhododendron, great	.....	.....	...	...	26	19
Sassafras	8,500	10,600	3.5	5.2	37	33
Serviceberry	12,200	21,000	4.1	9.6	63	59
Silverbell	9,100	13,300	3.3	6.0	27	24
Sourwood	10,800	17,200	4.1	8.6	38	38
Stopper, red	.....	.....	...	...	54	34
Sugarberry	8,200	11,600	3.2	5.4	33	36
Sumach, staghorn	.....	.....	...	...	..	..
Sycamore	8,800	10,500	3.3	3.9	26	26
Walnut, black	11,900	16,400	4.5	8.2	37	34
Walnut, little	9,900	11,100	4.5	4.5	46	21
Willow, black	5,100	7,700	2.0	3.6	36	20
Willow, western black	7,600	11,000	2.5	4.7	33	31
Witch-hazel	12,400	.....	6.3	...	40	..

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

† Air-dried to 12 percent moisture content.

TABLE 4. IMPACT-BENDING STRENGTH PROPERTIES OF AMERICAN WOODS*—*Continued*

Species	Stress at Proportional Limit, psi		Work to Proportional Limit, in.-lb./in.^{3}		Height of Drop Causing Complete Failure, in. (50-pound Hammer)	
	Green	Air-dry†	Green	Air-dry†	Green	Air-dry†
Softwoods						
Cedar, Alaska	9,100	12,200	3.2	5.0	27	29
Cedar, incense	7,300	9,600	2.4	3.9	17	17
Cedar, Port Orford	9,200	13,500	3.0	5.0	22	28
Cedar, eastern red	7,000	8,500	2.7	4.6	35	22
Cedar, southern red	10,500	10,200	5.4	4.2	18	17
Cedar, western red	6,900	8,600	2.5	3.2	17	17
Cedar, northern white	5,300	7,100	2.0	2.8	15	12
Cedar, southern white (Cedar, Atlantic white)	6,000	7,600	2.2	3.0	18	13
Cypress, southern (Cypress, bald)	8,800	10,400	3.3	3.9	25	24
Douglas fir (coast type)	9,800	12,700	3.2	4.5	24	30
Douglas fir (intermediate type)	8,700	11,600	2.7	4.4	22	27
Douglas fir (Rocky Mountain type)	9,100	12,100	3.0	4.8	20	26
Fir, alpine	5,300	7,000	1.6	2.3	9	16
Fir, balsam	6,900	7,800	2.3	2.6	16	20
Fir, corkbark	5,600	8,200	2.0	2.7	12	13
Fir, lowland white	8,100	12,000	2.6	4.6	22	28
Fir, noble	8,600	11,200	2.9	3.8	19	23
Fir, California red	8,600	12,000	2.8	4.3	22	23
Fir, silver	7,800	11,400	2.2	4.8	21	24
Fir, white	8,500	10,800	2.9	4.1	22	17
Hemlock, eastern	7,900	10,700	2.9	4.6	21	21
Hemlock, mountain	9,100	13,300	3.5	5.8	32	32
Hemlock, western	8,100	12,400	2.8	5.4	22	26
Juniper, alligator	6,800	5,600	3.9	2.5	21	12
Larch, western	9,400	15,100	3.7	7.3	24	32
Pine, jack	7,800	11,100	3.3	4.7	30	35

---

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

† Air-dried to 12 percent moisture content.

TABLE 4. IMPACT-BENDING STRENGTH PROPERTIES OF AMERICAN WOODS*—*Concluded*

Species	Stress at Proportional Limit, psi		Work to Proportional Limit, in.-lb./in.^{3}		Height of Drop Causing Complete Failure, in. (50-pound Hammer)	
	Green	Air-dry†	Green	Air-dry†	Green	Air-dry†
Softwoods						
Pine, Jeffrey	7,200	12,500	2.6	5.3	21	27
Pine, limber	7,100	11,400	2.6	5.2	18	19
Pine, loblolly	8,900	12,100	3.0	4.2	30	30
Pine, lodgepole	7,200	9,600	2.3	3.8	20	20
Pine, longleaf	10,100	15,400	3.2	6.1	35	34
Pine, mountain	10,200	14,200	3.8	6.4	29	29
Pine, northern white (Pine, eastern white)	6,700	9,500	2.2	3.7	17	19
Pine, Norway (Pine, red)	7,500	15,900	2.2	6.8	28	25
Pine, pitch	9,000	12,600	3.2	5.8	28	31
Pine, pond	9,400	13,200	3.2	5.0	33	28
Pine, ponderosa	6,800	9,800	2.5	4.0	20	17
Pine, sand	9,800	12,400	4.6	5.4	25	19
Pine, shortleaf	8,600	13,600	2.9	5.2	30	33
Pine, slash	10,800	15,800	3.9	5.8	36	36
Pine, sugar	7,400	10,700	2.6	4.4	17	18
Pine, western white	7,600	11,900	2.6	4.5	19	23
Pinyon	8,200	8,500	4.2	3.0	21	12
Redwood (virgin)	8,900	10,200	3.2	3.6	21	19
Redwood (second growth, openly grown)	5,900	6,800	2.3	2.7	14	11
Redwood (second growth, closely grown)	7,200	9,100	2.5	3.2	18	16
Spruce, black	6,800	13,400	1.8	6.2	24	23
Spruce, Engelmann	5,800	9,000	1.9	3.5	14	15
Spruce, red	7,200	11,900	2.3	4.6	18	25
Spruce, Sitka	8,400	11,400	3.0	4.2	24	25
Spruce, white	7,100	10,300	2.3	3.6	22	20
Tamarack	7,800	12,500	2.7	5.4	28	23
Yew, Pacific	13,100	12,100	6.2	5.5	38	31

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

† Air-dried to 12 percent moisture content.

and resistances. In making impact tests in the laboratory the test specimen is in reality a cushion between two impacting bodies, namely, the striking weight and the base of the machine. It is important that the mass of this base be sufficiently great that its relative velocity to that of the common center of gravity of itself and the striking weight may be disregarded.

4. It may deform the struck body as a whole against the resisting stresses developed by its own inertia, as, for example, when a baseball bat is broken by striking the ball.

Impact testing is difficult to conduct satisfactorily and the data obtained are of value chiefly in a relative sense, that is, for comparing the shock-resisting ability of woods of which like specimens have been subjected to identical treatment. Yet this test is one of the most important made on wood, as it brings out properties not evident from other tests. Defects and brittleness are revealed by impact better than by any other kind of test. In common practice nearly all external stresses are of the nature of impact. In fact, no two moving bodies can come together without developing impact stress. Impact is therefore the most common form of applied stress, although the most difficult to measure.

Strength of Wood as a Beam

The breaking strength of a beam is expressed in terms of stress per unit area by a *modulus of rupture* which is the computed maximum fiber stress in the extreme upper and lower surface fibers of the beam. Modulus of rupture is an approximation of the true stress, since assumptions on which the formula for computing it are based are valid only up to the proportional limit. However, the term is universally accepted, and for practical purposes the computed values are quite comparable for various species and sizes of timber. Values for modulus of rupture are used in calculating the strength of material to be used as beams and for deriving safe working stresses for joists, stringers, and like forms of wood (see pages 246–53).

The values for modulus of rupture (see Tables 1 and 2, col. 5) are usually derived from static-bending tests on small clear specimens, rectangular in cross section, freely supported at both ends and loaded at the center of the span (see pages 293–9 and Fig. 68). The following formula[30] is used:

$$R = \frac{1.5Pl}{bd^2} \tag{6}$$

in which

R = the modulus of rupture, pounds per square inch
P = the maximum load, pounds
l = the distance between supports (length of span), inches
b and d = the width and depth of the beam, respectively, inches[31]

---

[30] This equation is merely a special form of the flexure formula (equation 3) and is applicable only to simple beams, rectangular in cross section, supported at the ends and carrying a concentrated load at the center of the span. Under these conditions

$M = Pl/4$, $I = bd^3/12$, and $c = \frac{1}{2}$ depth of beam (d). $S = Mc/I$ then becomes

$$S = \frac{\frac{Pl}{4} \times \frac{d}{2}}{\frac{bd^3}{12}} = \frac{1.5Pl}{bd^2}$$

Since modulus of rupture (R) is the computed stress, $R = 1.5Pl/bd^2$.

[31] For other static loading conditions on rectangular prismatic beams, the following formulas are used:

(1) For small simple beams, uniformly loaded:

$$R = \frac{0.75Pl}{bd^2}$$

(2) For small simple beams, loaded at the third-points:

$$R = \frac{Pl}{bd^2}$$

(3) For large simple beams, loaded at the third-points (see Fig. 16), in which the weight of the beam is considered:

$$R = \frac{(0.75W + P)l}{bd^2}$$

in which W = the weight of the beam, pounds.

For cantilever and continuous beams, and beams fixed rigidly at one or both ends, as well as for different forms of cross section, and so on, other formulas are required (see any book on mechanics).

By transposing this formula it is evident that for rectangular prismatic simple beams of the same material, mode of support, and loading, the slowly applied load (P) that a given beam can support varies as follows:

1. It is inversely proportional to the length of span for beams of the same width and depth. Doubling the span reduces the load which the beam will support by half.
2. It is directly proportional to the width for beams of the same span and depth. If its width is doubled, a beam will support twice as much load.
3. It is directly proportional to the *square* of the depth for beams of the same span and width. If the depth of a beam is doubled, its breaking strength will be increased four times. It is on account of this relation of depth to bending strength that beams and similar forms of timber are usually placed on edge, with the wider faces vertical. However, if the depth of a member exceeds four times its width, there is a great tendency for the piece to twist when loaded. It is to overcome this tendency that floor joists are braced (cross-bridged) at frequent intervals.

In addition to modulus of rupture, values are also derived for *fiber stress at proportional limit* in static tests on small clear beams (see Tables 1 and 2, col. 4). Such values denote the stress in extreme fiber to which a beam may be subjected without exceeding the proportional limit; in other words, the maximum load the beam will support for a short time without acquiring a permanent deformation. Although it is indicative of the safe load that clear wood will support, fiber stress at proportional limit is not so reliable as modulus of rupture for computing safe working stresses. In calculating the fiber stress at proportional limit the same formula (equation 6) is used as for modulus of rupture, except that the load at proportional limit (P_1) is substituted for the maximum load (P).

STIFFNESS

The **stiffness** of wood, used either as a beam or long (or intermediate) column, is a measure of its ability to resist deformation or bending. It is expressed in terms of the *modulus of elasticity* and applies only within the proportional limit. Because of its orthotropic nature, wood is characterized by three moduli of elasticity, one for each structural direction (Fig. 2). Values for modulus of elasticity in the two directions perpendicular to the grain are relatively low, approximately $\frac{1}{20}$ to $\frac{1}{12}$ of the value parallel to the grain (see Table 5). Insofar as solid wood beams are concerned, the value for modulus of elasticity parallel to the grain is the only one of importance.

Modulus of elasticity values representative of the stiffness of beams are derived from static-bending tests[32] (see Tables 1 and 2, col. 6). They are used in calculating the deflection of beams, joists, stringers, and so forth, and in computing safe loads and working stresses for long and intermediate columns. The formula for the modulus of elasticity of a simple beam loaded at the center and resting freely on supports at either end is[33]

$$E = \frac{P_1 l^3}{48yI} \tag{7}$$

in which

E = modulus of elasticity, pounds per square inch
l = length of span (distance between supports), inches
y = maximum deflection at midspan, inches, corresponding to the load, P_1
P_1 = any load at or below the proportional limit, pounds
I = moment of inertia of the section, inches^4

For a beam of rectangular cross section this equation becomes

$$E = \frac{P_1 l^3}{4ybd^3} \tag{8}$$

in which b and d are the width and depth of the beam, respectively, in inches.

By transposing this formula it is evident that for rectangular beams of the same material, mode of support, and loading, the deflection y is affected as follows:

---

[32] Values for modulus of elasticity are also derived in a somewhat different manner from endwise compression tests on short columns (see pages 304–09 for method and formula). The values computed from such tests are similar to those obtained from static-bending tests when the bending specimens are long enough in relation to depth so that shear deformations are small; they are, however, somewhat higher than the values obtained from the standard static-bending specimens.

[33] Formulas and their derivation applicable to other types of loading are presented in C. C. Forsaith, *Technology of New York State timbers,* N. Y. State Col. For. Tech. publ. 18, Syracuse, 1926, pp. 185–219. See also any textbook on strength of materials.

1. It is directly proportional to the *cube* of the length of span for beams of the same width and depth. Tripling the span gives 27 times the deflection.

2. It is inversely proportional to the width for beams of the same span and depth. If the width is tripled, the deflection is one third as great.

3. It is inversely proportional to the *cube* of the depth for beams of the same span and width. If the depth is tripled, the deflection is $\frac{1}{27}$ as great. For this reason timbers are placed with the wider faces vertical where stiffness, as well as bending strength, is an important consideration.

The fact that the bending strength varies as the *square* of the depth and the stiffness as the *cube* of depth explains the relationship of bending to thickness. Were the ratio the same for strength and stiffness, a thin piece of wood, such as veneer, could not be bent any further without failure than a thicker piece, such as inch lumber.

The number of pounds that concentrated at the center will deflect a regular prismatic simple beam 1 inch may be found from the preceding formula by substituting $y = 1$ inch and solving for P_1.

The formula then becomes

$$\text{Necessary load } (P_1) = \frac{4Ebd^3}{l^3}$$

In this case the values for E are read from tables of average values prepared from data obtained by experimentation on the given material. It is essential, of course, that the load be within the proportional limit and that material be of average quality.

Although stiffness is independent of bending strength, woods which rank high in one respect also usually rank high in the other.

TOUGHNESS: SHOCK-RESISTING ABILITY

Toughness is a term that is commonly applied to more than one property of wood. Thus wood that is difficult to split is said to be tough. Again, a tough wood is one that will not rupture until it has deformed considerably under loads at or near its maximum strength,[34] or one that still hangs together after it has been ruptured and may be bent back and forth without breaking apart. In the sense in which it is used in this text, toughness is the ability of wood to absorb a relatively large amount of energy (work), or to endure the repetition of shocks or stresses (of very short duration) which exceed the proportional limit and produce permanent deformation and partial failure. It is the reverse of brittleness, in that tough woods break gradually and give warning of failure and is an especially important factor in determining the suitability of woods for striking tool handles, aircraft parts, and many types of athletic equipment. Coniferous woods, as a rule, are not so tough as hardwoods, of which hickory, ash, and oak are conspicuous examples.

Various types of tests are used in determining the toughness of wood. Chief of these is the increment-drop impact test, described on pages 299–304, from which values are obtained for *stress at proportional limit, work to proportional limit,* and *height of drop.* Although values for fiber stress at proportional limit in impact are not necessarily indicative of toughness, they have an advantage over the other properties named in that they represent a numerical measure that can be applied directly to the design of wooden members. Work to proportional limit and height of drop, on the other hand, are of value for comparative purposes only. Values for impact strength properties of a large number of American woods in the green and air-dry conditions are given in Table 4.

Work to the proportional limit in impact bending is a measure of the ability of a timber to absorb shock and recover therefrom immediately and without injury. The values apply only to conditions in which the stress is relieved after a duration of $\frac{1}{25}$ second or less. Height of drop (maximum drop of hammer) is a measure of the ability of wood to absorb energy under shocks that produce complete failure. It represents a quality important in articles that are occasionally stressed beyond their proportional limit, such as handles and vehicle and implement parts.[35]

Single-drop impact tests, in which the specimen is broken by a single blow, are also used in determining the ability of wood to absorb energy under shocks which produce complete failure.[36] This form of test is simpler than the increment-drop type and is consequently better adapted to making acceptance tests for the elimination of brittle and otherwise unsatisfactory material; it is less valuable for standard testing, however, since values for fiber stress at proportional limit and modulus of elasticity cannot be satisfactorily determined. A machine for making tests of this type, adapted from one originally designed by the Forest Products Laboratory, is described on pages 321–39[37] (see Fig. 88).

---

[34] In this sense the term is synonymous with flexibility.

[35] Newlin and Wilson, footnote 6, pp. 15–16, or Markwardt and Wilson, footnote 28, p. 14.

In addition to the strength properties derived from impact tests, the values for *work to proportional limit, work to maximum load,* and *total work,* as determined in static-bending tests on small clear beams, also indicate the relative shock-resisting ability of woods (see Tables 1 and 2, cols. 7, 8, and 9). Work to proportional limit is a measure of the work that a beam is able to resist, or the shock that it can absorb, without being stressed beyond the proportional limit as determined under slowly applied loads; that to maximum load represents the ability of timber to absorb shock with a slight permanent or semipermanent deformation of the material. The latter is a measure of the combined strength and toughness of a material under bending stresses.[38] Total work is a measure of the toughness of wood when loaded to complete failure in static bending. Values for these three properties are determined from the areas under the load-deflection curves obtained from static-bending tests, as indicated in Fig. 17 (see Resilience, page 6).

Another type of test sometimes used in determining the toughness of wood is the torsion or twisting test. If the ends of a shaft are turned in opposite directions, or one end is turned and the other is fixed, all the fibers except those at the axis tend to assume the form of helices. The strain produced by torsion or twisting is essentially shear combined with longitudinal tension and transverse compression. Within the proportional limit the strains increase directly as the distance from the axis of the specimen. The outer elements are subjected to tensile stresses and as they become twisted tend to compress those near the axis. The elongated elements also contract laterally. Cross sections that were originally plane become warped. With increasing strain the lateral adhesion of the outer fibers is destroyed, allowing them to slide past each other and reducing greatly their power of resistance. In this way the strains on the fibers nearer the axis are progressively increased until finally all the elements are sheared apart. It is only in the toughest materials that the full effect of this action can be observed. Brittle woods snap off suddenly with only a small amount of torsion, and their fracture is irregular and oblique to the axis of the piece instead of frayed out and more nearly perpendicular to the axis as with tough woods.

---

[36] For comparison of single-drop and increment-drop impact tests see Wilson, footnote 28.

[37] *Forest Products Laboratory toughness testing machine,* For. Prod. Lab. Rept. 1308, Madison, 1941.

[38] Newlin and Wilson, footnote 6, p. 15.

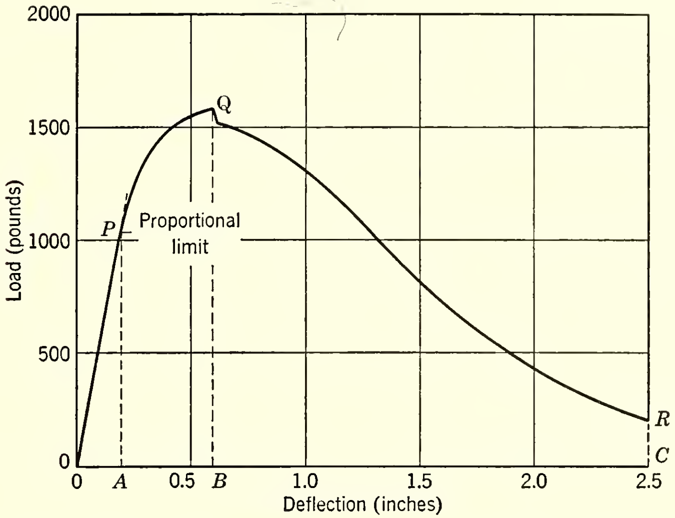


Fig. 17. Typical load–deflection curve for wood subjected to static bending. The areas *OPA*, *OQB*, and *ORC* represent values for work to proportional limit, work to maximum load, and total work, respectively.

HARDNESS

Hardness, as commonly used in connection with wood, is a measure of its resistance to indentation, although the term is also used to indicate the ability of the material to withstand abrasion or scratching. In the latter sense hardness combined with toughness is a measure of the wearing ability of wood and is an important consideration in the use of wood for floors, paving blocks, bearings, and rollers. Although resistance to indentation is dependent mostly on the density of the wood, the wearing qualities may be governed by other factors such as toughness, and the size, cohesion, and arrangement of the fibers. In use for floors, some woods tend to compact and wear smooth, whereas others become splintery and rough. This feature is affected to some extent by the manner in which the wood is sawed; thus edge-grain pine flooring is much better than flat-sawn for uniformity of wear.

The standard hardness test, made to determine the resistance of wood to indentation by a steel punch or ball (see pages 312–14 and Fig. 81), is of value for comparative purposes only. As a rule, there is little or no consistent difference between the hardness of the radial and tangential surfaces, but end hardness generally exceeds that determined from the sides of a piece (see Tables 1 and 2, cols. 13 and 14). For this reason, wood products in which hardness is the governing factor, such as paving blocks, are so used that the end grain is exposed to service loads. Tests for abrasion are also of comparative value only. These may be made by measuring the wear (loss of weight) of wood when scrubbed by sandpaper or other abrasive under controlled conditions.

CLEAVAGE RESISTANCE

Cleavage resistance is the term used to denote the resistance that wood offers to splitting. A splitting stress is one in which the forces act like a wedge (see Fig. 18). Low resistance to cleavage is very desirable in the preparation of firewood and of billets and squares. On the other hand, resistance to splitting, or poor cleavability, is desirable where wood must hold nails or screws.

Tests in cleavage are made to determine the force required to split specially prepared specimens (see pages 318–19 and Fig. 86*D*), the plane of cleavage being parallel to the grain and either radial or tangential. These tests are somewhat similar to those in tension perpendicular to the grain, but only a portion of the fibers are under stress at one time. The unit values obtained (pounds per inch of width of splitting surface) are of comparative value only. Tables 1 and 2 (col. 16) give the results of cleavage tests on American woods in the green and air-dry conditions.

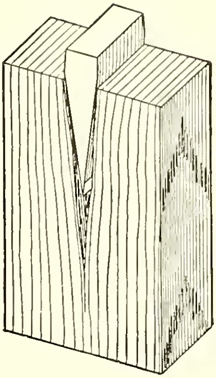


FIG. 18. Cleavage of a straight-grained, stiff wood. The cleft runs far ahead of the wedge.

Most woods split more readily along the rays than parallel to the growth rings. As might be expected, this difference is most marked in woods in which the rays are highly developed, such as oak, sycamore, and beech. A marked exception to this general rule is to be found in woods with interlocked grain. When such woods are split radially, the distorted fibers are more or less inclined to the plane of cleavage, so that their pronounced strength in tension parallel to the grain is brought into play. A wood of little stiffness and strong cohesion across the grain is difficult to split, whereas one of great stiffness, such as longleaf pine, is easily split.

ELASTIC PROPERTIES OF WOOD

Except for modulus of elasticity parallel to grain, data relating to the elastic constants of wood have been determined for only a few species. Although not ordinarily used in solid wood design, values for elastic constants applicable to the three axes of symmetry of wood (Fig. 2) are important in the design of plywood, sandwich-type panels, and similar constructions.

The elastic constants of eleven species are shown or may be computed from ratios shown in Table 5.

Moduli of elasticity (*Young's moduli*) **perpendicular to the grain** are designated as E_T in the direction of the tangential axis and E_R in the direction of the radial axis (Fig. 2). These values are indicated in Table 5 as ratios of modulus of elasticity parallel to the grain (E_L). Although considerable variation among species is shown, Young's modulus in the radial direction is consistently greater than the corresponding value in the tangential direction.

TABLE 5. ELASTIC PROPERTIES OF WOOD*

Species	Specific Gravity	Moisture Content, %	Young's Modulus in Longitudinal Compression, E_L, 1000 psi	Young's Modulus Ratios		Modulus of Rigidity Ratios			Poisson's Ratios					
				$\frac{E_T}{E_L}$	$\frac{E_R}{E_L}$	$\frac{G_{LR}}{E_L}$	$\frac{G_{LT}}{E_L}$	$\frac{G_{RT}}{E_L}$	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}
Ash†	0.80	13.6	2180	0.064	0.109	0.057	0.041	0.0165	0.533	0.653	0.656	0.386	0.058	0.042
Balsa	0.14	9.5	550	0.015	0.046	0.054	0.037	0.005	0.229	0.488	0.665	0.231	0.018	0.009
Birch, yellow	0.64	13	2075	0.050	0.078	0.074	0.067	0.0169	0.426	0.451	0.697	0.426	0.043	0.024
Douglas fir	0.51	13‡	2280	0.050	0.068	0.064	0.078	0.007	0.292	0.449	0.390	0.374	0.036	0.029
Gum, red	0.54	11	1696	0.050	0.115	0.089	0.061	0.020	0.325	0.403	0.682	0.309	0.044	0.023
Mahogany														
African (Khaya)	0.45	11.3	1478	0.050	0.111	0.088	0.059	0.021	0.297	0.641	0.604	0.264	0.033	0.032
Central American	0.50	11.7	1654	0.064	0.107	0.086	0.066	0.028	0.314	0.533	0.600	0.326	0.033	0.034
Poplar, yellow	0.38	11	1407	0.043	0.092	0.075	0.069	0.011	0.318	0.392	0.703	0.329	0.030	0.019
Quipo	0.13	11.8	235	0.055	0.182	0.082	0.055	0.032	0.216	0.666	0.455	0.128	0.047	0.032
Spruce, Sitka	0.38	12.8	1688	0.043	0.078	0.064	0.061	0.003	0.372	0.467	0.435	0.245	0.040	0.025
Walnut†	0.59	11.0	1630	0.056	0.106	0.085	0.062	0.0036	0.495	0.632	0.718	0.367	0.052	0.036

* With the exception of data for ash and walnut, values are taken from *Elastic properties of wood,* For. Prod. Lab. Repts. 1528 and 1528A-H, 1945–46.

† Values from Table 2–5, ANC Bul. 18, *Design of wood aircraft structures,* Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1944, based on work of C. F. Jenkin, *Report on materials used in aircraft and aircraft engines,* Aero. Res. Comm., Great Britain, 1920.

‡ Modulus of rigidity ratios for Douglas fir determined at 11 percent moisture content for wood with specific gravity of 0.44.

Modulus of rigidity (sometimes called *modulus of elasticity in shear*) is designated by the symbol G. Moduli of rigidity associated with shear deformations in different planes are denoted by subscripts, thus G_{LT} is the modulus of rigidity associated with shear deformations in the LT (tangential) plane resulting from shear stresses in the LR (radial) and RT (cross-sectional) planes. G_{LR} is the modulus associated with shear deformations in the radial plane resulting from shear stresses in the other two planes, and G_{RT} is the modulus associated with shear deformations in the cross-sectional plane. Ratios of modulus of rigidity to modulus of elasticity parallel to grain (E_L) are presented in Table 5. G_{LR} is generally slightly greater than G_{LT} and both of these are many times greater than G_{RT}.

Poisson's ratio is the ratio of the expansion along one of the structural axes to the contraction occurring in the direction of stress as a result of a compressive stress acting parallel to another axis on a cube of wood. It is designated as μ. In Table 5 six values of μ are given, each corresponding to the directions of stress and lateral deformation involved. For example, μ_{LT} refers to the expansion in the tangential direction corresponding to a compressive stress in the longitudinal direction, and μ_{TL} refers to the expansion in the longitudinal direction corresponding to a compressive stress in the tangential direction.

REFERENCES

American Society for Testing Materials: Standard methods of testing small clear specimens of timber. Serial Designation: D143-48, 1948 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

Betts, H. S.: *The strength of North American woods.* U. S. Dept. Agr. Misc. Publ. 46, Washington, 1929.

Boyd, J. E.: *Strength of materials.* 4th ed. rev. McGraw-Hill Book Co., New York, 1935.

Dewell, Henry D.: *Timber framing.* Dewey Publ. Co., San Francisco, 1917.

Forest Products Laboratory: *Wood handbook,* rev. U. S. Dept. Agr. Unnumbered Publ., Washington, 1940.

———: *Design of wood aircraft structures.* ANC Bul. 18, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1944.

———: *Elastic properties of wood.* For Prod. Lab. Repts. 1528 and 1528A-H, Madison, 1945–46.

Forsaith, C. C.: *The technology of New York State timbers.* N. Y. State Coll. For. Tech. Publ. 18, Syracuse, 1926.

JACOBY, HENRY S., and ROLAND P. DAVIS: *Timber design and construction.* 2d. ed. John Wiley & Sons, New York, 1930.

JOHNSON, J. B.: *The materials of construction.* 8th ed., rewritten by M. O. Withey and James Aston. John Wiley & Sons, New York, 1939.

KOEHLER, ARTHUR: *The properties and uses of wood.* McGraw-Hill Book Co., New York, 1924.

KOLLMANN, FRANZ: *Technologie des Holzes.* Julius Springer, Berlin, 1936.

LAURSON, P. G., and W. J. COX: *Mechanics of materials.* 2d ed. John Wiley & Sons, New York, 1947.

MARKWARDT, L. J.: *Comparative strength properties of woods grown in the United States.* U. S. Dept. Agr. Tech. Bul. 158, Washington, 1930.

——— and T. R. C. WILSON: *Strength and related properties of woods grown in the United States.* U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935.

MCELHANNEY, T. A., and ASSOCIATES: *Canadian woods: their properties and uses.* Canada Dept. Int., Ottawa, 1935.

MOORE, HERBERT F.: *Textbook of the materials of engineering.* 7th ed. McGraw-Hill Book Co., New York, 1947.

NEWLIN, J. A., and J. M. GAHAGAN: *Tests of large timber columns and presentation of the Forest Products Laboratory column formula.* U. S. Dept. Agr. Tech. Bul. 167, Washington, 1930.

——— and T. R. C. WILSON: *Mechanical properties of woods grown in the United States.* U. S. Dept. Agr. Bul. 556, Washington, 1917.

PARKER, HARRY: *Simplified design of structural timber.* John Wiley & Sons, New York, 1948.

RECORD, SAMUEL J.: *Mechanical properties of wood.* John Wiley & Sons, New York, 1914.

PART 2

Factors Affecting the Mechanical Properties of Wood

Wood is an intricate natural structure designed to serve the functional needs of a living plant. It differs in pattern and properties, not only according to the genus and species of the tree that produces it, but also in response to changes in the current and local requirements of growth of the individual.[1]

As indicated in the foregoing tables, the various species offer markedly different resistances to forces tending to deform them. The tabulated values, however, are merely the *average* results of tests on clear specimens selected to represent the different woods. They do not indicate the range of variability within a given species, which experience has shown may be greater, as evidenced by extremes of individual pieces, than that between the average values of relatively strong and weak woods.

Just why specimens of a given kind of wood cut from different trees, or even pieces from the same log, should often exhibit pronounced dissimilarity in density and in the strength of the clear wood is not always evident, but to a large extent these variations may be attributed to the numerous and changing environmental conditions under which the wood was produced. Further, the strength of specific timbers and other forms of wood is influenced by various other factors, chief among which are the presence of defects and the treatment the material received in preparing it for use.

It follows that, in judging the suitability of wood for uses where strength is an essential requirement, full consideration should be given to the factors influencing the quality of wood, especially those that can be determined by visual inspection or simple test. In this way, the use of defective or inherently weak material may be avoided to a large extent.

---

[1] For details as to variation in the anatomy of the common American woods see Samuel J. Record, *Identification of the timbers of temperate North America,* John Wiley & Sons, New York, 1934.

Also H. P. Brown, A. J. Panshin, and C. C. Forsaith, *Wood technology, Vol. I, Structure, identification, defects, and uses of the commercial woods of the United States,* McGraw-Hill Book Co., New York, 1948.

DEFECTS

For the purposes of this discussion, a **defect,** in wood, is defined as any irregularity occurring in or on wood that may lower its strength.[2] Based on their relative weakening effect, such irregularities are divided into two groups, namely, major and minor defects. Major defects consist of knots, checks, shakes, splits, cross grain, compression failures, cross breaks, decay, and compression wood, all of which may seriously impair the strength of wood and should be rigidly controlled as to extent and location in the grading and use of structural timbers and other material in which strength is of vital importance. Minor defects include pitch pockets, bark pockets, pitch and pitch streaks, frost splits or cracks, frost rings, lightning rings, insect holes, gum spots, black streaks, pith flecks, burls, ring distortions, bird peck, warping in its various forms, casehardening, honeycombing, collapse, pith, and wane. These latter irregularities are normally not considered serious from the standpoint of their relation to the strength of wood and are usually limited for other reasons than their weakening effect. Not infrequently, however, such minor flaws may indicate the presence of more serious defects. Thus, warping may be indicative of cross grain, numerous pitch pockets may indicate the presence of general shakes, and bark pockets may be indicative of concealed knots.

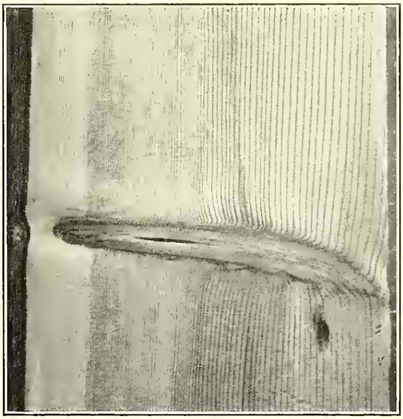
Knots

Knots, the most prevalent defects in structural timber, are portions of the main branches or smaller limbs included in the wood of the bole of a tree. As long as they remain alive, the branches, which generally originate at the pith, or growth center of the stem,[3] increase in size beyond the periphery of the trunk by the addition of annual layers of wood. On the underside of a branch these annual layers are distinctly continuous with those of the bole, thus affording an unbroken path for the flow of soil moisture from the roots to the leaves of the branch; on the upper side the grain of the bole is interrupted and tends to pass around the branch, making an imperfect connection with it. As a result, the direction of the fiber in and around the knot is at right angles or oblique to the grain of the stem, thus producing local cross grain (see Fig. 19).

---

[2] The definitions of the various defects given in the following pages are in agreement with those adopted by the American Society for Testing Materials. See Definitions of terms relating to timber, Serial Designation: D9-30, 1930 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

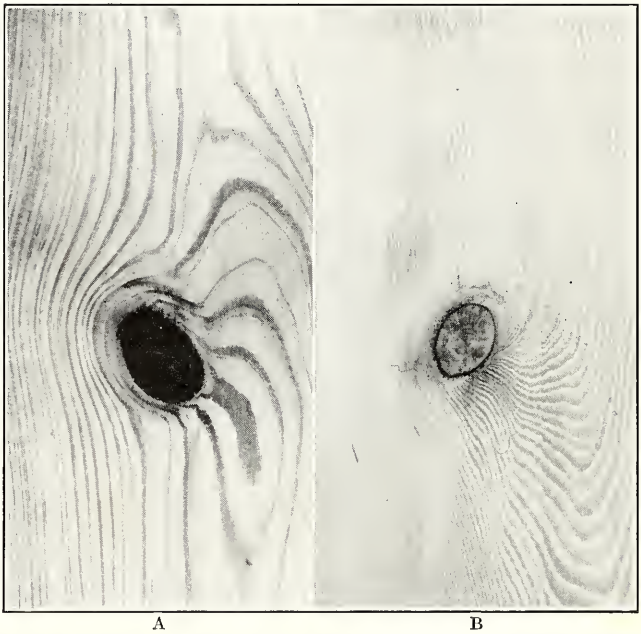
[3] Adventitious branches may have their origin at some distance from the pith, but they are usually of rare occurrence in forest-grown material.



Forest Products Laboratory Photo

FIG. 19. Spike knot showing distortion of grain. The annual layers of growth in the adjoining wood are distinctly continuous with those of the knot so long as the branch remains alive and that portion of the knot is *intergrown.* After the death of the branch, there no longer remains any continuity with the surrounding wood, and the knot is *encased.*

Because of the nature of the origin and subsequent growth of the branches, the knots are irregularly conical in shape, with their tips at the pith of the stem. Consequently, in considering the effect of knots, it should be borne in mind that the portion exposed in sawing merely represents a section of this conical mass. The shape of the exposed portion will, of course, vary with the direction through which the knot is cut. When a section passes at right angles or more or less obliquely to the axis of a knot, a *round* (or *oval*) *knot* results (Fig. 20*A*), whereas a section passing lengthwise through it gives rise to a *spike knot* (Fig. 19). As long as a limb remains alive, its layers of growth are directly connected with those of the stem, and the resultant knot, which is said to be *intergrown* (Fig. 19), is firmly fixed in the surrounding wood. But, during the development of a tree, particularly when it is growing under crowded conditions in the forest, the lower limbs usually die and, although they generally persist for a number of years, their cambium (growth zone) ceases to function. In consequence, the fibers of the stem are no longer intimately joined with those of the dead limb. Instead they are laid around the base of the branch encasing it and showing a decrease in grain distortion. A dead branch results in what is known as an *encased knot* (Fig. 20*B*) which is, in effect, nothing more than a peg in a hole and is likely to become loose and even drop out after the tree has been sawed into lumber, particularly when the branches have been infected with decay. Knots are classified according to size, form, quality, and occurrence.[4]



Forest Products Laboratory Photo

FIG. 20. *A*. Intergrown round knot in yellow pine. *B*. Encased knot in hemlock.

---

[4] Definitions of terms relating to timber, footnote 2.

Eventually the dead branches may break at or near the periphery of the tree trunk, owing to weakening by decay or other causes, resulting in what is termed "natural pruning." Likewise, both live and dead branches may be removed by artificial means. As the trunk of the tree continues its diameter growth, the newly formed growth rings close in about the end of the broken or pruned stub, and it is finally healed over by subsequent growth. When this condition is reached, grain distortion ceases as new layers of wood are laid down, and the succeeding growth produces clear lumber at this point.

Knots materially affect checking and warping, ease in working, and cleavability of timber. They are defects that also depreciate the value of wood for structural purposes and other uses where strength is an important consideration. Their weakening effect, however, is brought about not by any inherent inferiority of the material composing them, but rather by the combined effect of the local cross grain which they produce and the checking which may develop in and around them in drying. In resistance to tension, it has been found that intergrown knots are fully as injurious as knot holes or encased knots of the same size. The greater distortion of the grain around an intergrown knot and the more pronounced checking may more than offset the strength reduction resulting from the absence of material in a knot hole or the lack of attachment in an encased knot. In resistance to sidewise compression, however, sound knots are less injurious, since the wood of such defects is normally decidedly harder than the surrounding material.

The stiffness of beams is largely dependent on the quality of the wood fiber and, as a rule, is not materially affected by knots of the sizes normally encountered in structural lumber.[5] However, in small members in which the steep cross grain associated with a knot constitutes a major portion of the cross section, considerable reduction in stiffness has been noted.[6] Breaking

---

Also *Lumber,* Simplified Practice Recommendation R16-39, U. S. Dept. Comm., Washington, 1940, pp. 28–9.

And Edward P. Ivory, David G. White, and Arthur T. Upson, *Standard grading specifications for yard lumber,* U. S. Dept. Agr. Dept. Circ. 296, Washington, 1923, pp. 63–4. Contains 22 plates showing standard defects.

[5] L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935, pp. 68–9.

[6] N. V. Poletika, Effect of local cross grain on the stiffness of small beams,

strength, on the other hand, is greatly influenced by knots, the effect of which is to reduce the difference between the fiber stress at proportional limit and the modulus of rupture of beams.[7]

In structural timbers subjected to bending, the precise influence of knots on strength is largely a matter of their location in the piece and the resultant kind of stress to which they are exposed, although the degree to which they alter the direction of the grain of the wood, their number, and the extent to which they are checked also play an important part. Knots on the convex side of a loaded beam are subjected to tension, those on the concave side to compression, and those midway between the two sides to horizontal shear. Resistance to tension is materially reduced by any marked distortion of the grain at the surface of the piece, since tensile strength at right angles to the grain is only a small fraction of that parallel to the grain. Checking will further reduce such resistance. In consequence, knots located at or near the point of greatest tensile stress in a timber have a serious effect on its strength. In compression, however, the weakening effect of the local cross grain is decidedly less than in tension, and checking in and around the knot is also less injurious.[8] In horizontal shear knots exert little or no influence; in fact they may even slightly increase the resistance to this stress by breaking up the continuity of checks that materially reduce shearing strength.

Since tension and compression stresses in a timber subjected to bending are greatest at the center of the convex and concave sur-

---

Jour. For., Washington, July 1947, pp. 511–12. A continuation of this study involved the fabrication of beams containing cross-grain inserts to permit mathematical analysis of the effect of cross grain on stiffness. See N. V. Poletika, A new method for studying the elastic behavior of wood, *Wood*, Chicago, June 1948, pp. 26–8, 58, and July 1948, pp. 26, 28, 30, 51–2.

[7] McGarvey Cline and A. L. Heim, *Tests of structural timbers,* U. S. Dept. Agr. For. Serv. Bul. 108, Washington, 1912, pp. 52–4.

[8] "The influence that a knot on the tension face at the point of maximum moment exerts on the strength of a green beam is approximately measured by the ratio of the diameter of the knot to the width of the face. The diameter of the knot is measured between lines parallel to the edges of the face. That is, a knot one-fourth the width of the face will reduce the strength 25 percent. The same knot on the compression side would have about one-half this influence. Large knots have a somewhat greater influence on the strength than is indicated by this rule, owing to the relatively large distortion of the grain around them."—J. A. Newlin, Unit stresses in timber, *Proc. Am. Soc. Civil Eng.,* New York, Vol. 52, Sept. 1926, p. 1440.

faces, respectively, and decrease toward the neutral plane and ends, it is evident that knots are most weakening when located in the middle portion of the tensile side, less so in the central portion of the compression side, and least weakening if situated midway between the two surfaces or near the ends of the timber. These various factors of position, as well as those of size, have at various times been taken into consideration in the application of grading rules to structural timbers.[9]

The effect of knots on columns is dependent on the length of the timber as well as on the size and location of the defects. In long columns, where stiffness is the governing factor, their effect on strength is relatively small. In intermediate and short columns the reduction in strength because of the presence of knots is approximately proportional to the knot size, although, as in the case of beams, large knots have a somewhat greater effect in reducing strength in relation to their size than smaller ones. In other words, the effect of the knots is practically the same as removing a similar amount of clear material from the cross section. Further, when the piece contains a number of knots, occurring either singly or in whorls, the effect of all knots within any 6 inches of length is practically the same as if they occurred at the same height and in the same plane.[10]

Checks and Shakes

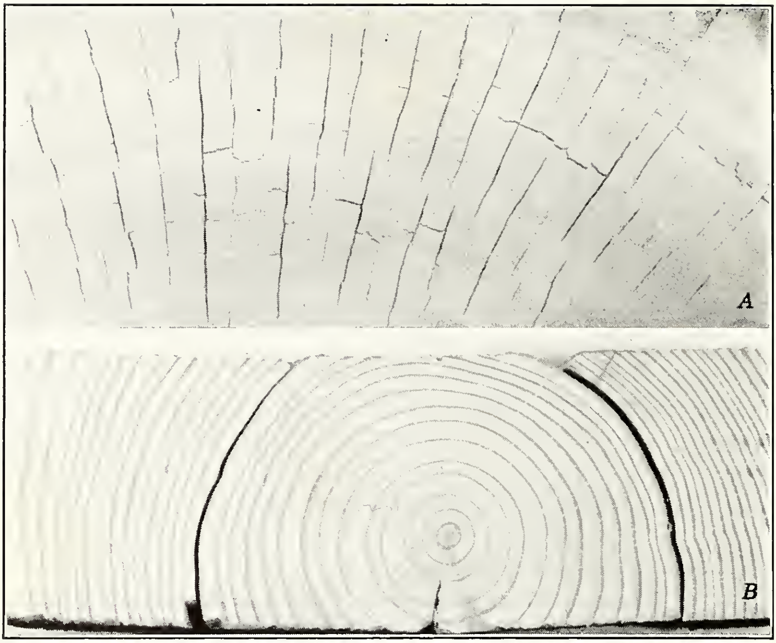
A **check** is defined as a separation of the wood along the grain, the greater part of which extends across the annual-growth rings in the direction of the rays (Fig. 21*A*); **shake** is a separation along the grain, the greater part of which occurs between and parallel to the rings of growth (Fig. 21*B*). Checks commonly result from the unequal shrinkage that takes place in the wood during seasoning and are classified as *surface checks* and *end checks.*[11]

---

[9] See pages 220–1 and Fig. 54.

[10] J. A. Newlin and J. M. Gahagan, *Tests of large timber columns and presentation of the Forest Products Laboratory column formula,* U. S. Dept. Agr. Tech. Bul. 167, Washington, 1930, pp. 2, 20–1.

[11] A third type of check, known as *heart check,* is also recognized in timbers that include the pith. In this the split starts at or near the pith and extends toward but not to the surface of the piece. Where several of these occur together, a *star check* is formed. Although these separations of the wood are classified as checks because they occur across the growth rings, they are actually comparable to shakes, being formed in the wood before the tree is felled and not as a result of seasoning.



Yale Photo

FIG. 21. *A*. Checks resulting from end drying. *B*. Shake.

Shakes represent the rupture of the cells in certain weak portions of the wood, due to uncertain causes, and are often termed *ring* or *cup shakes.* Shakes seldom develop unless they were present to a certain degree in the tree before it was felled. **Splits** are lengthwise separations, extending from one surface through the piece to another surface, produced in wood as a result of rough handling or internal stresses. They affect the strength of the wood in the same way as checks and shakes.

FORMATION OF CHECKS

The walls of the cells in wood are made up of a multitude of very minute, spirally inclined and more or less longitudinally directed, thread-like aggregrates known as *fibrils.* The fibrils, in turn, are made up of *microfibrils* consisting of a network of

---

Still another form of checking is the interior checking, or *honeycombing,* that infrequently develops in casehardened lumber. This is discussed under Miscellaneous Seasoning Defects.

micelles, or *crystallites,* that are in general oriented in a direction parallel to the fibril axis. In unseasoned wood the cell walls are saturated, and these micelles are slightly separated by films of water. The cells, and the wood itself, are at their maximum (and normal) volume. Any *free water* that is present in the cell cavities has no effect on the size of the cells. But, as the wood seasons and the cell walls begin to lose their *hygroscopic moisture,*[12] the micelles are drawn closer together, with the result that the dry wood cells are smaller in cross section and have thinner walls than when wet. Their length, however, remains fairly constant, since the more or less axially inclined particles can produce little or no longitudinal contraction of the walls as they approach one another. If the shrinkage of the different cells coincided and took place uniformly throughout a piece of wood, there would be no undue stresses set up in the stick, and checking would not result. But for several reasons this is impossible. Variations in the amount of shrinkage which takes place in the different directions with respect to the grain of the wood, lack of uniformity in the rate of drying between the inside and the outside of a stick and between its ends and the portions further back, and dissimilarity in density in different parts of the same piece are all responsible for the unequal shrinkage that inevitably occurs as wood seasons and gives rise to the stresses commonly resulting in the checking of wood.

There is a marked difference in the longitudinal, radial, and tangential shrinkage of wood. In general the longitudinal shrinkage is very slight, varying in normal, straight-grained woods from about $\frac{1}{10}$ to $\frac{1}{3}$ of 1 percent of their length in drying from the unseasoned to the oven-dry condition.[13] In contrast to this, the shrinkage at right angles to the grain is quite pronounced, ranging from approximately 2 to 8 percent of the original unseasoned size in the radial direction and from about 4 to 14 percent in the tangential, as indicated in Table 6. Since the figures shown in this table apply to oven-dried material, the shrinkage in air-dried and kiln-dried wood will be proportionately less, depending on the amount of moisture lost below the fiber-saturation point. The ratio of tangential to radial shrinkage in individual woods ranges, as shown, from slightly more than 1¼ to 1 in such woods as paper and yellow birch and certain of the pines to a maximum of 3 to 1 in black willow.

---

[12] When a wood cell dries, there is no loss of moisture from its walls until all the free water in the cell cavity has been removed. The stage at which the cell cavities are completely devoid of moisture but the walls are still fully saturated is known as the *fiber-saturation point.* It is at this point that shrinkage begins as wood is dried. The fiber-saturation point varies in the different species and even in different pieces of the same kind of wood. It has an extreme range of 20 to 35 percent moisture content but in most woods occurs between 25 and 30 percent.

[13] In the abnormally dense *compression wood* and in certain light pieces, in which longitudinal shrinkage is more pronounced, the fibrils in the cell walls form a more decided angle with the long axis of the cells than is normally the case, thus resulting in greater lengthwise contraction of the individual fibers and of the wood when drying takes place. In cross-grained

In order to understand the reasons for this variation in shrinkage, it is necessary to consider the arrangement of the elements in the wood. All normal wood cells become smaller in cross section on drying but undergo little change in length, as has already been explained. But they do not all extend in the same direction in the tree or piece of wood, and, consequently, their shrinkage does not coincide in all directions. Microscopic examination of American woods reveals the fact that their ground mass is composed largely of wood fibers (in the hardwoods) or tracheids (in conifers), which extend longitudinally or with the grain of the wood. Hence, these cells in drying tend to decrease the cross section of a stick both radially and tangentially but do not affect its length to any extent.[14] A portion of every wood is made up of rays,[15] the individual cells of which usually have their longest axis lying in the radial direction, that is, extending across the growth rings at right angles to the grain. According to one theory, shrinkage of these ray cells thus tends to shorten a piece of wood longi-

---

material the oblique alignment of the cells in the wood results in more pronounced endwise shrinkage.

For further discussion see Arthur Koehler, *Longitudinal shrinkage of wood,* Paper presented at the Fifth Nat. Conference, Am. Soc. Mech. Eng., Wood Ind. Division, New York, 1930.

Also R. A. Cockrell, Explanation of longitudinal shrinkage of wood based on interconnected chain molecule concept of cell-wall structure, *Trans. Am. Soc. Mech. Eng.,* New York, Nov. 1947, pp. 931–5.

[14] Vessels and wood parenchyma cells also extend in the same direction as the fibers and tracheids and act in a similar manner.

[15] In pine, over 15,000 of these rays occur on a square inch of tangential section, whereas in oak the very large rays, which may be several inches high and are readily visible to the unaided eye as flakes on quarter-sawed (edge-grain) surfaces, represent scarcely one percent of the number the microscope reveals.

TABLE 6. WEIGHT AND SHRINKAGE OF AMERICAN WOODS*

Species	Weight per cubic foot, lb.		Shrinkage from Green to Oven-Dry Condition, Based on Green Dimensions, %		
	Unseasoned	At 12 percent moisture content	Volumetric	Radial	Tangential
Hardwoods					
Alder, red	46	28	12.6	4.4	7.3
Apple	55	47	17.6	5.6	10.1
Ash, Biltmore	45	38	12.6	4.2	6.9
Ash, black	52	34	15.2	5.0	7.8
Ash, blue	46	40	11.7	3.9	6.5
Ash, green	49	40	12.5	4.6	7.1
Ash, Oregon	46	38	13.2	4.1	8.1
Ash, pumpkin	46	36	12.0	3.7	6.3
Ash, white	48	42	13.3	4.9	7.9
Aspen	43	26	11.5	3.5	6.7
Aspen, largetooth	43	27	11.8	3.3	7.9
Basswood	42	26	15.8	6.6	9.3
Beech	54	45	16.3	5.1	11.0
Beech, blue (Hornbeam, American)	53	49	19.1	5.7	11.4
Birch, Alaska white	48	38	16.7	6.5	9.9
Birch, gray	46	35	14.7	5.2	..
Birch, paper	50	38	16.2	6.3	8.6
Birch, sweet	57	46	15.6	6.5	8.5
Birch, yellow	57	43	16.7	7.2	9.2
Blackwood	74	58	15.6	6.2	9.7
Buckeye, yellow	49	25	12.0	3.5	7.8
Bustic	77	62	..	..	..
Butternut	46	27	10.2	3.3	6.1
Buttonwood	64	50	14.6	5.4	8.5
Cascara	50	36	7.6	3.2	4.6
Catalpa, hardy	41	29	7.3	2.5	4.9
Cherry, black	45	35	11.5	3.7	7.1
Cherry, pin	33	27	12.8	2.8	10.3
Chestnut	55	30	11.6	3.4	6.7
Chinquapin, golden	61	32	13.2	4.6	7.4
Cottonwood, eastern	49	28	14.1	3.9	9.2

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

TABLE 6. WEIGHT AND SHRINKAGE OF AMERICAN WOODS*—*Continued*

Species	Weight per cubic foot, lb.		Shrinkage from Green to Oven-Dry Condition, Based on Green Dimensions, %		
	Unseasoned	At 12 percent moisture content	Volumetric	Radial	Tangential
Hardwoods					
Cottonwood, northern black	46	24	12.4	3.6	8.6
Dogwood	64	51	19.9	7.1	11.3
Dogwood, Pacific	55	45	17.2	6.4	9.6
Elder, blueberry	65	36	15.6	4.4	9.0
Elm, American (Elm, white)	54	35	14.6	4.2	9.5
Elm, rock	53	44	14.1	4.8	8.1
Elm, slippery	56	37	13.8	4.9	8.9
Fig, golden	51	31	..	..	..
Gum, black (Tupelo, black)	45	35	13.9	4.4	7.7
Gum, blue	70	52	22.5	7.6	15.3
Gum, red (Gum, sweet)	50	34	15.0	5.2	9.9
Gum, tupelo (Tupelo, water)	56	35	12.5	4.2	7.6
Gumbo limbo	38	21	8.6	2.3	3.6
Hackberry	50	37	13.8	4.8	8.9
Haw, pear	64	47	..	..	..
Hickory, bigleaf shagbark	62	48	19.2	7.6	12.6
Hickory, bitternut	63	46	..	..	..
Hickory, mockernut	64	51	17.9	7.8	11.0
Hickory, nutmeg	60	42	..	..	..
Hickory, pignut	63	52	17.9	7.2	11.5
Hickory, shagbark	64	50	16.7	7.0	10.5
Hickory, water	68	43	..	..	..
Holly	57	40	16.2	4.5	9.5
Honeylocust	61	..	10.8	4.2	6.6
Hophornbeam	60	49	18.6	8.2	9.6
Inkwood	71	56	18.8	6.6	10.9
Ironwood, black (Leadwood)	86	81	11.6	6.2	8.0

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U.S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

Table 6. Weight and Shrinkage of American Woods*—*Continued*

	Weight per cubic foot, lb.		Shrinkage from Green to Oven-Dry Condition, Based on Green Dimensions, %		
Species	Unseasoned	At 12 percent moisture content	Volumetric	Radial	Tangential
Hardwoods					
Laurel, California	54	39	11.9	2.8	8.1
Laurel, mountain	62	48	14.4	5.6	8.0
Locust, black	58	48	9.8	4.4	6.9
Madrono, Pacific	60	45	17.4	5.4	11.9
Magnolia, cucumber	49	33	13.6	5.2	8.8
Magnolia, evergreen	59	35	12.3	5.4	6.6
Magnolia, mountain	47	31	13.0	4.4	7.5
Mangrove	77	67	15.8	5.4	..
Maple, bigleaf	47	34	11.6	3.7	7.1
Maple, black	54	40	14.0	4.8	9.3
Maple, red	50	38	13.1	4.0	8.2
Maple, silver	45	33	12.0	3.0	7.2
Maple, striped	37	32	12.3	3.2	8.6
Maple, sugar	56	44	14.9	4.9	9.5
Mastic	77	65	11.7	6.1	7.5
Oak, black	62	43	14.2	4.5	9.7
Oak, bur	62	45	12.7	4.4	8.8
Oak, California black	66	40	12.1	3.6	6.6
Oak, canyon live	71	54	16.2	5.4	9.5
Oak, chestnut	61	46	16.7	5.5	9.7
Oak, laurel	65	44	19.0	4.0	9.9
Oak, live	76	62	14.7	6.6	9.5
Oak, Oregon white	69	50	13.4	4.2	9.0
Oak, pin	63	44	14.5	4.3	9.5
Oak, post	63	47	16.2	5.9	9.8
Oak, northern red	63	44	13.5	4.0	8.2
Oak, Rocky Mountain white (Oak, Gambel)	62	51	12.5	4.1	7.2
Oak, scarlet	62	47	13.8	4.6	9.7
Oak, southern red	62	41	16.3	4.5	8.7
Oak, swamp red	68	47	16.4	5.2	10.8
Oak, swamp chestnut	65	47	19.4	5.9	9.2

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

TABLE 6. WEIGHT AND SHRINKAGE OF AMERICAN WOODS*—*Continued*

Species	Weight per cubic foot, lb.		Shrinkage from Green to Oven-Dry Condition, Based on Green Dimensions, %		
	Unseasoned	At 12 percent moisture content	Volumetric	Radial	Tangential
Hardwoods					
Oak, swamp white	69	50	17.7	5.5	10.6
Oak, water	63	44	16.4	4.2	9.3
Oak, white	62	48	15.8	5.3	9.0
Oak, willow	67	48	18.9	5.0	9.6
Osage-orange	62	..	8.9	..	..
Palmetto, cabbage	54	27	25.0	..	..
Paradise tree	38	24	8.6	2.2	5.2
Pecan	61	46	13.6	4.9	8.9
Persimmon	63	52	18.3	7.5	10.8
Pigeon-plum	73	55	15.7	4.4	7.8
Poisonwood	54	37	11.6	4.2	7.2
Poplar, balsam	40	23	10.5	3.0	7.1
Poplar, yellow	38	28	12.3	4.0	7.1
Rhododendron, great	62	40	16.2	6.3	8.7
Sassafras	44	31	10.3	4.0	6.2
Serviceberry	61	52	18.7	6.7	10.8
Silverbell	44	32	12.6	3.8	7.6
Sourwood	53	38	15.2	6.3	8.9
Stopper, red	72	61	13.3	6.2	9.1
Sugarberry	48	36	12.7	5.0	7.3
Sumach, staghorn	41	33	..	..	..
Sycamore	52	34	14.2	5.1	7.6
Walnut, black	58	38	11.3	5.2	7.1
Walnut, little	55	40	10.7	4.4	4.6
Willow, black	50	26	13.8	2.5	7.8
Willow, western black	50	31	13.8	2.9	9.0
Witch-hazel	59	43	18.8	..	..
Softwoods					
Cedar, Alaska	36	31	9.2	2.8	6.0
Cedar, incense	45	..	7.6	3.3	5.2

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U.S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

Table 6. Weight and Shrinkage of American Woods*—*Continued*

	Weight per cubic foot, lb.		Shrinkage from Green to Oven-Dry Condition, Based on Green Dimensions, %		
Species	Unseasoned	At 12 percent moisture content	Volumetric	Radial	Tangential
Softwoods					
Cedar, Port Orford	36	29	10.1	4.6	6.9
Cedar, eastern red	37	33	7.8	3.1	4.7
Cedar, southern red	33	31	7.0	2.2	4.0
Cedar, western red	27	23	7.7	2.4	5.0
Cedar, northern white	28	22	7.0	2.1	4.7
Cedar, southern white (Cedar, Atlantic white)	26	23	8.4	2.8	5.2
Cypress, southern (Cypress, bald)	51	32	10.5	3.8	6.2
Douglas fir (coast type)	38	34	11.8	5.0	7.8
Douglas fir (intermediate type)	38	31	11.2	4.2	7.4
Douglas fir (Rocky Mountain type)	35	30	10.6	3.6	6.2
Fir, alpine	28	23	9.0	2.5	7.1
Fir, balsam	45	25	10.8	2.8	6.6
Fir, corkbark	29	21	9.0	2.6	6.9
Fir, lowland white	45	28	10.6	3.2	7.2
Fir, noble	30	26	12.5	4.5	8.3
Fir, California red	48	27	11.8	3.8	6.9
Fir, silver	36	27	14.1	4.5	10.0
Fir, white	47	26	9.4	3.2	7.0
Hemlock, eastern	50	28	9.7	3.0	6.8
Hemlock, mountain	44	33	11.4	4.4	7.4
Hemlock, western	41	29	11.9	4.3	7.9
Juniper, alligator	42	36	7.8	2.7	3.6
Larch, western	48	36	13.2	4.2	8.1
Pine, jack	50	30	10.4	3.4	6.5
Pine, Jeffrey	47	28	9.9	4.4	6.7

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

TABLE 6. WEIGHT AND SHRINKAGE OF AMERICAN WOODS*—*Concluded*

Species	Weight per cubic foot, lb.		Shrinkage from Green to Oven-Dry Condition, Based on Green Dimensions, %		
	Unseasoned	At 12 percent moisture content	Volumetric	Radial	Tangential
Softwoods					
Pine, limber	39	28	8.2	2.4	5.1
Pine, loblolly	53	36	12.3	4.8	7.4
Pine, lodgepole	39	29	11.5	4.5	6.7
Pine, longleaf	55	41	12.2	5.1	7.5
Pine, mountain	54	36	10.9	3.4	6.8
Pine, northern white (Pine, eastern white)	36	25	8.2	2.3	6.0
Pine, Norway (Pine, red)	42	34	11.5	4.6	7.2
Pine, pitch	50	34	10.9	4.0	7.1
Pine, pond	49	38	11.2	5.1	7.1
Pine, ponderosa	45	28	9.6	3.9	6.3
Pine, sand	38	34	10.0	3.9	7.3
Pine, shortleaf	52	36	12.3	4.4	7.7
Pine, slash	58	43	12.2	5.5	7.8
Pine, sugar	52	25	7.9	2.9	5.6
Pine, western white	35	27	11.8	2.6	5.3
Pinyon	51	37	9.9	4.6	5.2
Redwood (virgin)	50	28	6.8	2.6	4.4
Redwood (second growth, openly grown)	43	21	6.3	2.0	4.4
Redwood (second growth, closely grown)	42	24	7.4	2.4	5.0
Spruce, black	32	28	11.3	4.1	6.8
Spruce, Engelmann	39	23	10.4	3.4	6.6
Spruce, red	34	28	11.8	3.8	7.8
Spruce, Sitka	33	28	11.5	4.3	7.5
Spruce, white	35	28	13.7	4.7	8.2
Tamarack	47	37	13.6	3.7	7.4
Yew, Pacific	54	44	9.7	4.0	5.4

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, 1935, Table 1.

tudinally and tangentially, but not radially (in the direction of their length). It has been suggested, therefore, that the contraction of the various cells in the wood coincides in the tangential direction, whereas radially and longitudinally the rays act in opposition to the other elements. Hence, according to this theory, although tangential shrinkage takes place unhindered, the radial contraction of the fibers and other longitudinally disposed cells is retarded to some extent by the endwise reaction or thrust of the ray cells. More recently, differential shrinkage in the radial and tangential directions has been attributed to differences in the orientation of the submicroscopic structural units of the cell wall, specifically to a more nearly longitudinal fibrillar orientation in the tangential cell walls.[16]

Shrinkage stresses tending to cause checks are developed when wood is dried below the fiber-saturation point. However, the strength of the individual cells, the cohesion between them, and their ability to make adjustments in shape, thus relieving internal stress, are usually sufficient to prevent such failures when wood dries gradually. But, when the stresses produced in this way are augmented by those resulting from too rapid drying on the sides or ends of a piece, the natural resistance of the wood is overcome, and separations, or checks, occur in the planes of weakness along the wood rays.

If, in the process of drying wood, the evaporation of moisture from the surface were accompanied by a suitable rate of transfusion of water from the interior, shrinkage would be uniform thoroughout the piece, at least insofar as it is affected by moisture content. In well-controlled kiln drying this hypothetical condition may be approximated, but in air seasoning, and often in ordinary kiln drying, transfusion usually lags, and the surface layers reach the fiber-saturation point and begin to shrink considerably before the more slowly drying interior. As a result tensile stresses are set up in this drier outer shell of wood which may be sufficiently great to tear the fibers apart, producing *surface checks* (see Figs. 23 and 24). On the other hand, if the intensity of these stresses does not exceed the resistance of the wood, the surface tends to become "set" without full shrinkage taking place, giving rise, when the interior dries, to the *casehardened* condition discussed under Miscellaneous Seasoning Defects. Surface checks occur chiefly along the rays, for the reasons already mentioned and, consequently, are observed on the tangential surfaces. Such checks usually do not penetrate far into the wood, although they may be more pronounced in timbers and other large-sized material than in thinner lumber, owing to the greater difference between the moisture content of the interior and exterior portions of the more sizable material. As the interior of the wood dries out, they may close, but their weakening effect remains.

---

[16] Evidence contradictory to the theory that wood-ray cells tend to oppose longitudinal elements in their shrinkage has been presented by G. J. Ritter and R. L. Mitchell, Crystal arrangement and swelling properties of fibers and ray cells in basswood holocellulose, *Paper Trade Jour.* Feb. 9, 1939, pp. 33–7. See also A. Frey-Wissling, Die Anistropie des Schwindmasses auf dem Holzquerschnitt, *Holz als Roh—und Werkstoff*, Berlin, Vol. 3, 1940, pp. 43–5. Also A. J. Stamm and W. K. Loughborough, Variation in shrinking and swelling of wood, *Trans. Am. Soc. Mech. Eng.*, New York, May 1942, pp. 379–86.

In the storage of logs and in drying lumber, timbers, cross ties, and the like, the ends lose moisture more rapidly than the sides, not only because moisture travels along the grain more readily than across it, but also because the ends of the material piled for seasoning are more exposed to drying conditions than the portions in the interior of the pile.[17] The more rapid drying of the ends causes local shrinkage, and were the material sufficiently plastic, the ends would become bluntly tapered. The rigidity of the wood substance prevents this, however, and the cells are split apart, resulting in *end checking* (see Fig. 21*A*). Later, as the remainder of the stick dries many of the checks will close, though some of the largest will remain and may even increase in size as the drying proceeds. End checks normally follow the rays, since these are the natural planes of weakness in the wood, but occasionally they also extend tangentially (along the growth rings) as a result of the separation of the thin-walled springwood cells. These tangential checks, however, are less pronounced and not so serious as the normal radial failures.

Variations in the density of different portions of a piece of wood may also affect the uneven shrinkage and resultant checking that occurs in drying, although this factor is of far less consequence than those already discussed. Since density is largely dependent on the amount of actual wood substance, it is evident that the heavier parts of a given stick will tend to shrink more than the lighter ones.[18] Consequently, when marked variations in density occur in different parts of the same piece, owing to decided changes in rate of growth or other causes, the shrinkage may be more uneven than would otherwise be the case.

---

[17] Despite this fact, the loss of moisture is far greater from the sides of a stick, because the amount of surface area thus exposed is so much greater than on the ends. Only in unpeeled products, in which the bark retards surface drying, is an appreciable portion of the total moisture removed from the ends.

It has been suggested that in ring-porous hardwoods and in those conifers that exhibit distinct differences in density between early and late wood, the greater contraction of denser wood is in some measure responsible for the fact that tangential shrinkage is greater than radial. In these woods the denser bands of late wood are continuous in the tangential direction, whereas radially they are separated by alternate zones of less dense early wood. However, the ratio of tangential to radial shrinkage is decidedly greater in northern white pine and black willow, which exhibit little difference in density between early and late wood, than in longleaf pine and white oak in which the difference between the two portions of the growth ring is quite marked. That other similar comparisons might be made is evidenced in Table 6.

The use of anticheck irons to prevent end checking of cross ties and poles during air seasoning is now a common practice in the United States, particularly in stock piled for seasoning prior to preservative treatment. These devices are driven into the butts of the timbers so as to cross incipient checks and prevent their

---

[18] The following equations, representing the average relations between density and the shrinkage that takes place in drying wood from the unseasoned to the oven-dry condition, have been worked out at the Forest Products Laboratory:

$$\begin{aligned}\text{Radial shrinkage} &= 9.5G\\ \text{Tangential shrinkage} &= 17.0G\\ \text{Volumetric shrinkage} &= 28.0G\end{aligned}$$

where G is the specific gravity, based on oven-dry weight and unseasoned volume, and shrinkage is expressed as percentage of dimensions when unseasoned. From J. A. Newlin and T. R. C. Wilson, *The relation of the shrinkage and strength properties of wood to its specific gravity,* U. S. Dept Agr. Bul. 676, Washington, 1919.

These equations apply, in general, not only within the same species but also between different kinds of wood, although in the latter case notable exceptions are found in Table 6.

widening. Other methods of reducing the end checking of wood during air seasoning consist of shading the ends of the piles, nailing small wood or metal cleats to the ends of the boards, or painting the ends with some moisture-retardant coating. This last method is also adapted to kiln drying, in which end checking may also be reduced by the maintenance of a fairly high humidity.

In air seasoning it is difficult to prevent surface checking although it may be reduced by close piling or otherwise cutting down the circulation within the pile. Care must be taken, however, to see that the drying conditions are not reduced to such an extent that the air within the pile becomes more or less stagnant, since this condition will entirely prevent the drying of the wood and may invite decay. In kiln drying, surface checking may be entirely eliminated by proper humidity control.

FORMATION OF SHAKES

Shakes are commonly observed in unseasoned as well as seasoned timber, being formed in the tree before falling and not as a result of seasoning, although the stresses set up in drying may cause the shakes to enlarge materially. *Ring shake* results from the partial or complete separation of two growth rings (see Fig. 21*B*). It is common in hemlock, sycamore, western larch, and a few other woods, and may occur in any species. It is most frequently found at the junction of two growth rings of very unequal width. Consequently it is likely to occur in trees that have grown slowly for a time, then shown an abrupt increase in rate of diameter growth, as a result of thinning or other treatments which improve the growing conditions. Old timber is more subject to shake than are young trees, and this defect is usually confined to the butt log.

The causes of cup or ring shake are uncertain. The swaying action of the wind is frequently held responsible for the splitting or shearing apart of the growth rings, especially in trees growing in exposed places, and for this reason the failure is sometimes known as *wind shake*. The defect, however, often occurs in trees protected from the wind and is not necessarily confined to the portion of the tree where the greatest shear stresses are developed. Frost may in some instances be responsible for shake, or at least be a contributing factor, although trees growing in regions free from frost may also develop the defect. Koehler has advanced the theory that shakes are caused by transverse compressive and tensile stresses resulting from growth, and are not due primarily to bending.[19] Possible causes of such stresses include (1) greater proportionate circumferential than radial growth, (2) reduction in turgidity of older tissues, and (3) chemical shrinkage of older wood.

A localized defect somewhat similar in effect to shake is known as *rind gall.* If the cambium layer is exposed by the removal of the entire bark or rind, it will die. Subsequent growth over the damaged portion does not cohere with the wood previously formed by the cambium. The defect resulting is termed rind gall. The most common causes of it are fire, gnawing by rodents or other animals, blazing, chipping, sun scald, lightning, and abrasions.

Heart shake occurs commonly in overmature timber, being more frequent in hardwoods (especially oak) than in conifers. While essentially a shake it is usually classified as *heart check,* since the separations extend across the growth rings instead of between them. In typical heart shake the center of the bole shows indications of becoming hollow and radial clefts of varying size extend outward from the pith, being widest inward. This defect frequently affects only the butt log, where it is sometimes associated with ring shake, although it may also extend to the entire bole and even the larger branches. It is thought to result from growth stresses.[19] When it consists of a single cleft across the pith it is termed *simple heart shake* (or *check*), while an aggregate of several such radial separations is known as *star shake* (or *check*). In unseasoned timber these clefts may extend outward from the pith for several inches, but in felled or converted timber they tend to open up more and more as the wood seasons and may reach nearly to the bark or the surface of the piece.

Effect of Checks and Shakes on Strength

The effect of checks and shakes on the fundamental strength properties of tension, compression, and shear is summarized as follows:[20]

---

[19] Arthur Koehler, A new hypothesis as to the cause of shakes and rift cracks in green timber, *Jour For.,* Washington, May 1933, pp. 551–6.

[20] J. A. Newlin and R. P. A. Johnson, Structural timbers—defects and their influence on strength, *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 24, Pt. 2, 1924, pp. 975–87.

Tension. "The separation of the wood fibers by checks has little, if any, effect upon the strength in tension when the load is applied in line with the fibers. On the other hand, when the load is applied perpendicular to the fibers their separation by checks will cause a direct reduction of the area acting in resistance to tension and, consequently, will reduce the strength. The reduction in tensile strength from checking varies between these two extremes, becoming more and more serious as the angle of grain increases.

"As in the case of checks, shakes have no effect on tensile properties when the load is applied in line with the grain, but any separation of the annual rings would, of course, destroy the tensile strength across the grain."

Compression. "The effect of checks and shakes is confined largely to causing an unequal distribution of stresses which results in a reduction of strength through the overstressing of some of the fibers before others . . . and failures therefore occur at somewhat lower average loads than if the checks were not present."

Shear. "Reduction in shearing strength is due almost entirely to the presence of shakes and checks. Weakening in shear from checks and shakes consist in a direct reduction of the area acting in resistance to shear. Moreover, shakes are usually accompanied by a general weakness in bond between the annual growth rings, which seriously affects the shear strength." This weakness usually extends far beyond the point of actual separation of the rings.

It is evident that the weakening effect of checks and shakes on beams and other members subjected to bending is largely dependent on their proximity to the neutral plane, since it is there that the horizontal-shearing stresses are at the maximum. On the tension (convex) and compression (concave) faces they exert little, if any, effect, except where checking occurs in conjunction with knots or other forms of local cross grain.[21]

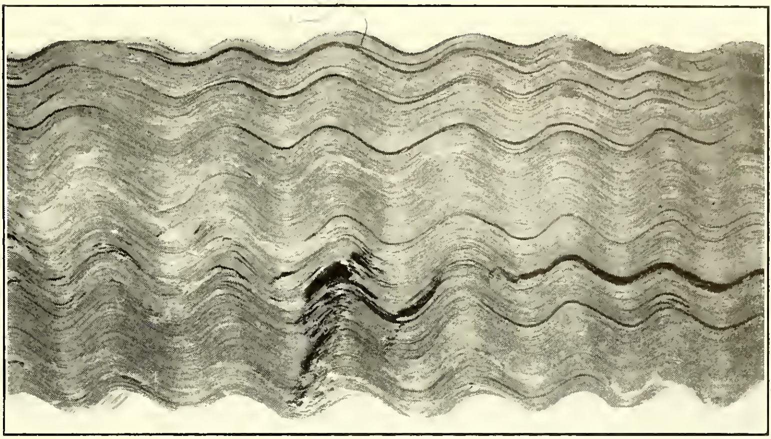
Cross Grain

Cross-grained wood is defined as that in which the wood cells or fibers run at an angle with the axis, or sides, of the piece.

---

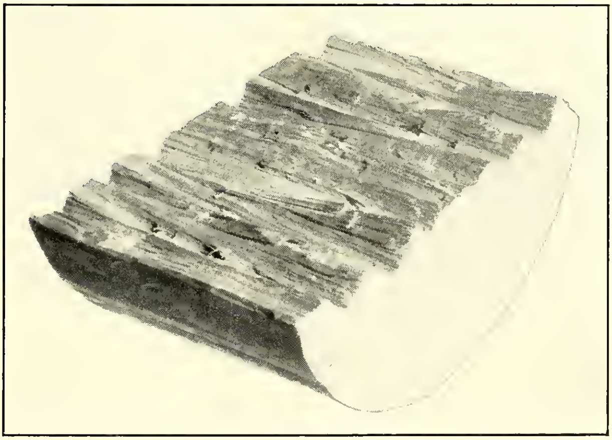
[21] For specific limitations placed on checks, shakes, and splits in grading structural timbers, see pages 230–2.

Several forms of cross grain are recognized—spiral, diagonal, wavy (Fig. 22*A*), dip, and interlocked grain (Fig. 22*B*)—but



Forest Products Laboratory Photo

Fig. 22*A*. Wavy grain in redwood (tangential surface).



Forest Products Laboratory Photo

Fig. 22*B*. Interlocked grain in tupelo.

only the first two are normally considered as important defects in structural timbers. Consequently, the limits on cross grain where strength is involved are intended to apply primarily to spiral and diagonal grain.[22,23]

SPIRAL GRAIN

Spiral grain is a very common defect in many timbers and when excessive greatly reduces their structural strength. It is produced naturally in the living tree by a somewhat abnormal alignment of the wood cells, which, instead of being approximately parallel to the axis of the stem or branch, are laid down in a spiral arrangement about it. The twist may be either right-handed or left-handed, although the former is more common, and in a given tree may vary in degree and direction at different heights in the bole, as well as from the pith outward to the bark[24] (see Fig. 23).

As to the cause of spiral grain there is much conjecture, and various theories have been offered to explain the phenomenon. The influence of wind in particular, and of light and gravity, singly and in combination, as well as soil and other local conditions, have been held up as contributing causes. A theory sometimes advanced considers the obliquity of the fibers as a method of accommodating the increase in length of the cells after their formation in the cambium. An attempt has been made to link up the twisting of the tree trunk with the root system, the claim being advanced[25] that trees with tap roots exhibit no twist, those with lateral roots have it to a slight degree, whereas those with running roots possess marked spiral grain. Although the cause of spiral grain has never been satisfactorily explained, there is some evidence to show that the defect is capable of being transmitted from generation to generation.[26]

---

[22] For definitions, discussion, and illustrations of other forms of cross grain see Arthur Koehler, *The properties and uses of wood,* McGraw-Hill Book Co., New York, 1924, pp. 22–8.

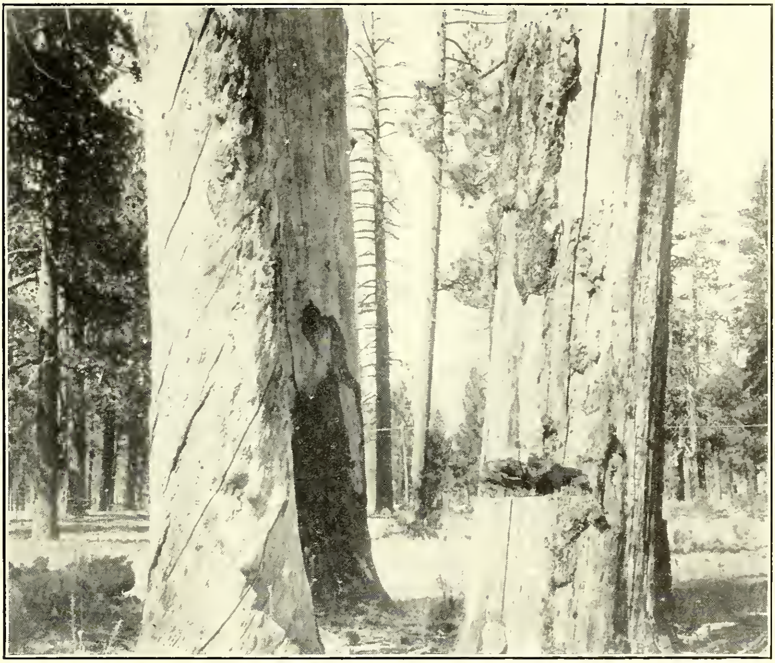
[23] Ivory, White, and Upson, footnote 4, p. 60 and Plates VI–VII.

[24] See Edward F. McCarthy and Raymond J. Hoyle, Knot zones and spiral in Adirondack red spruce, *Jour. For.,* Washington, Vol. 16, Nov. 1918, pp. 777–91.

[25] Paul van Oye, Sur la torsion des troncs d'arbres, *Bul. Soc. Bot. France,* Vol. 73, 1926, pp. 270–88.

[26] See H. G. Champion, Contributions towards a knowledge of twisted fiber in trees, *Indian For. Records,* Silvicultural Ser., Calcutta, Vol. 11, Pt. 2, 1925.

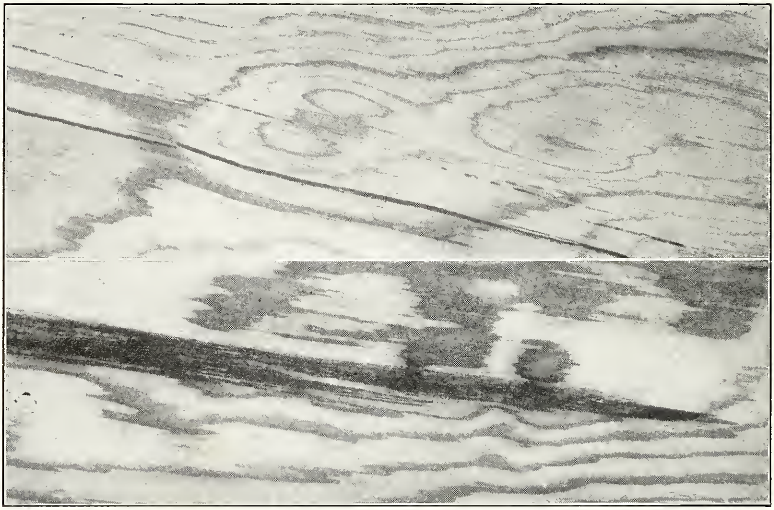
Spiral grain often cannot be detected by casual inspection of a stick, since it does not show on the so-called visible grain of the wood, by which is meant a sectional view of the annual rings of growth cut longitudinally (radial or edge-grain surface). It is accordingly very easy to allow spiral-grained material to pass inspection, thereby introducing an element of weakness in a structure. There are, however, methods of readily detecting this defect. The simplest is that of splitting a piece at right angles to the growth rings, as the cleft will follow the grain and the split surfaces will be more or less twisted if the grain is spiral. It is necessary that the split be across the growth rings and not tangent to them, as in the latter case it is quite probable that the wood would split straight.



Forest Products Laboratory Photo

FIG. 23. Spiral grain and straight grain in ponderosa pine trees. Grain direction is indicated by the checks in these dead trees from which the bark has been removed.

Splitting, of course, mutilates the piece and is consequently an impractical method of determination in many cases. In the careful inspection of those woods in which the rays, vessel lines, and resin ducts are prominent,[27] the alignment of these elements, as observed on the flat-grain (tangential) surface, affords a ready index to the presence or absence of spiral grain. These elements all extend parallel to the fibers and will be vertical or inclined according to the straight- or spiral-grained character of the wood. On a smooth, tangential section, reflected light will often reveal the direction of the fibers themselves, whereas on the edge-grain (radial) faces of finished material the inclination of fibers pulled out by the planer often serves the same purpose.



Forest Products Laboratory Photo

FIG. 24. Spiral grain revealed by surface checks and resin ducts (top) and by a pitch streak (bottom).

Checks, which develop in seasoning and follow along the rays for the most part, are factors of considerable importance in the determination of spiral grain on tangential surfaces (see Fig. 24). This is particularly true with poles and posts and other material used in the round, spiral-grained specimens of which commonly show prominent checks running spirally around them.

---

[27] Even in those woods in which these elements are not distinct on tangential section, close scrutiny, particularly with a hand lens, will often reveal their alignment. A scribe consisting of a phonograph needle or other sharp-pointed object, suitably mounted, may also be used for this purpose. See Arthur Koehler, *Guide to determining slope of grain in lumber and veneer,* For. Prod. Lab. Rept. 1585, Madison, 1943.

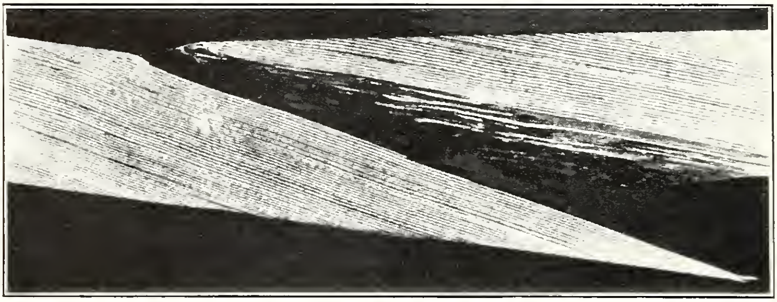
The presence of spiral grain is recognized as a serious defect in sawed material and, for this reason, products in which straight grain is essential to meet exacting strength requirements are often made from billets and squares that are split out of the log rather than being sawed. In timber used in the round, on the other hand, this type of defect is usually not considered serious. However, in such material, spiral grain may be objectionable because of its tendency to cause twisting of a piece; it is accordingly limited in standard specifications for wood poles.

Diagonal Grain

Diagonal grain is produced in lumber entirely by the method of sawing and has no reference to the natural alignment of the wood elements. Thus, in cutting plain-sawed lumber, if the plane of the saw is not approximately parallel to the bark surface, the grain of the wood is not parallel to the edges and is termed diagonal. This may occur as the result of careless sawing, as well as in cutting crooked logs and those with swelled butts. It also results from the common practice of sawing logs, having pronounced taper, parallel to the axis of growth instead of parallel to the bark.

Although spiral grain is usually indiscernible on the edge-grain (radial) surface, except when the piece is split radially, diagonal grain is most evident on that face. It sometimes happens, however, that a piece is sawed so that the fibers are not parallel to the axis of the piece on a flat-grain (tangential) surface. In such a case, a phenomenon somewhat similar to natural spiral grain is produced, and the piece is said to be *artificially spiral grained.* This form of cross grain can be distinguished from true spiral by observing the character of the surface when the piece is split radially, but, since its effect on the strength of wood is similar to that of true spiral grain, it is commonly classified as such.

In those woods having conspicuous rings of growth, both the presence and slope of diagonal grain are indicated on the edge-grain surfaces by the direction of the growth rings (see Fig. 25), whereas on the flat-grain faces the presence but not the slope of diagonal grain may be shown by the numerous parabolas produced by the intersection of the growth rings with the surface. In woods having indistinct growth rings both the direction and slope may be determined by splitting the pieces tangentially, or by observing on the radial surface the inclination of vessel lines or resin ducts, the direction in which ink spreads, or the direction of fibers as indicated by scribe marks.[28] Diagonal grain is more readily detected than spiral and, therefore, not so apt to be overlooked on inspection.



Forest Products Laboratory Photo

FIG. 25. Typical bending failure due to diagonal grain (Douglas fir).

MEASUREMENT OF CROSS GRAIN

In order to estimate the effect of cross grain on the various strength properties of wood, it is necessary to have some measure of its degree. This is afforded by the *slope* of the cross grain, by which is meant the deviation of the grain from the edge of the stick or from a line parallel to its main axis. This slope may be expressed in several ways, but it is usually designated by the ratio between a 1-inch deviation of the grain from the edge of a piece and the distance along the edge over which this deviation occurs. Thus a slope of 1 in 20 means that in a distance of 20 inches along the edge of a stick the grain deviates 1 inch from the edge.

When a piece has both spiral and diagonal grain, it is not sufficient to consider the greater slope of the two as the measure of the effect of the cross grain. The true effect is computed by taking the square root of the sum of the squares of the slopes of the two forms of cross grain. Thus, if the slope of the diagonal grain (as observed on radial surface) is 1 in 15 and that of the spiral grain (on tangential surface) 1 in 20, the true or absolute slope = $\sqrt{(1/15)^2 + (1/20)^2} = 1/12$, or a slope of 1 in 12. The true slope of grain resulting from other combinations of spiral and diagonal grain is shown in Table 7. It has been shown by tests that the weakening effect of combined diagonal and spiral grain is approximately the same as that of either form having the same absolute slope. It has also been demonstrated that spiral grain is no more weakening than diagonal grain of the same slope, although spiral-grained material is more subject to checking than is diagonal-grained.

---

[28] Koehler, footnote 27.

Measurement of spiral and diagonal grain may be somewhat complicated on sticks that present neither true radial nor tangential surfaces. In rectangular lumber, however, the combined slope may be readily determined by measuring the slope of fibers as shown on two adjoining faces and substituting these slopes in Table 7 to obtain the true slope of grain for the piece.[29]

EFFECT OF CROSS GRAIN ON STRENGTH

In beams subjected to bending, the weakening effect of cross grain shows a wide variation with respect to the three fundamental strength properties—tension, compression, and shear. Since the ratio of the tensile strength of wood parallel to the grain to that at right angles to the grain ranges from about 25 to 1 in unseasoned wood to as high as 45 to 1 in air-dry material, it is apparent that the slightest deviation from straight grain will tend to reduce the strength of the wood. However, this decrease in tensile strength does not become appreciable until a slope of 1 in 25 is reached. In compression, the effect of cross grain is less marked, since the strength parallel to the grain in both unseasoned and air-dry material is only 3 to 10 times that perpendicular to it, and the slope approaches 1 in 10 before a decided decrease in compressive strength is evident. In shear, the weakening effect of cross grain is usually negligible; in fact, it may even increase the shearing strength by breaking up the continuity

---

[29] Methods for measuring slope of grain are discussed in detail by Koehler, footnote 27.

TABLE 7. COMBINED SLOPE OF SPIRAL AND DIAGONAL GRAIN*

How to Determine Combined Slope of Spiral and Diagonal Grain

First, determine slopes of spiral and of diagonal grain separately. To determine the combined or resultant slope, find the column headed by the greater of the two slopes, and in this column locate the figure in line with the lesser of the two slopes as given in the left-hand column. This figure represents the length in inches in which the grain deviates 1 inch with respect to the central axis of the piece.

Example. If the slope of spiral grain is 1 in 20 and the slope of diagonal grain is 1 in 25, the combined slope is 1 in 15.6.

	Slope of Spiral or Diagonal Grain, Whichever Is Greater																			
Slope of Spiral or Diagonal Grain, Whichever Is Lesser	*1–10*	*1–11*	*1–12*	*1–13*	*1–14*	*1–15*	*1–16*	*1–17*	*1–18*	*1–19*	*1–20*	*1–21*	*1–22*	*1–23*	*1–24*	*1–25*	*1–26*	*1–27*	*1–28*	*1–29*
1–10	7.1																			
1–11	7.4	7.8																		
1–12	7.7	8.1	8.5																	
1–13	7.9	8.4	8.8	9.2																
1–14	8.1	8.7	9.1	9.5	9.9															
1–15	8.3	8.9	9.4	9.8	10.2	10.6														
1–16	8.5	9.1	9.6	10.1	10.5	10.9	11.3													
1–17	8.6	9.2	9.8	10.3	10.8	11.2	11.7	12.0												
1–18	8.7	9.4	10.0	10.5	11.1	11.5	12.0	12.4	12.7											
1–19	8.8	9.5	10.1	10.7	11.3	11.8	12.2	12.7	13.1	13.4										
1–20	8.9	9.6	10.3	10.9	11.5	12.0	12.5	13.0	13.4	13.8	14.1									
1–21	9.0	9.7	10.4	11.1	11.6	12.2	12.7	13.2	13.7	14.1	14.5	14.9								
1–22	9.1	9.8	10.5	11.2	11.8	12.4	12.9	13.5	13.9	14.4	14.8	15.2	15.6							
1–23	9.2	9.9	10.6	11.3	12.0	12.6	13.1	13.7	14.2	14.6	15.1	15.5	15.9	16.3						
1–24	9.2	10.0	10.7	11.4	12.1	12.7	13.3	13.9	14.4	14.9	15.4	15.8	16.2	16.6	17.0					
1–25	9.3	10.1	10.8	11.5	12.2	12.9	13.5	14.1	14.6	15.1	15.6	16.1	16.5	16.9	17.3	17.7				
1–26	9.3	10.1	10.9	11.6	12.3	13.0	13.6	14.2	14.8	15.3	15.9	16.3	16.8	17.2	17.6	18.0	18.4			
1–27	9.4	10.2	11.0	11.7	12.4	13.1	13.8	14.4	15.0	15.5	16.1	16.6	17.1	17.5	17.9	18.3	18.7	19.1		
1–28	9.4	10.2	11.0	11.8	12.5	13.2	13.9	14.5	15.1	15.7	16.3	16.8	17.3	17.8	18.2	18.6	19.1	19.4	19.8	
1–29	9.5	10.3	11.1	11.9	12.6	13.3	14.0	14.7	15.3	15.9	16.5	17.0	17.5	18.0	18.5	18.9	19.4	19.8	20.1	20.5

*Based on formula: Combined slope of grain $= \sqrt{(\text{slope of spiral grain})^2 + (\text{slope of diagonal grain})^2}$

From Arthur Koehler, *Guide to determining slope of grain in lumber and veneer*, For. Prod. Lab. Rept. 1585, 1943.

of any checks that develop in the critical section of the beam.[30]

A series of tests were conducted at the Forest Products Laboratory to determine the effect of cross grain (spiral and diagonal) on the strength of wood.[31] Sitka spruce, Douglas fir, and commercial white ash were subjected to static and impact bending and white ash alone to compression parallel to the grain. Table 8 shows the average percentage by which this material, with varying slopes of grain, fell below straight-grained material in various strength properties. A comparison of these three species with respect to the influence of slope of grain on modulus of rupture, modulus of elasticity, and work to maximum load, all in static bending, and maximum drop in impact bending indicates that there is relatively little difference between the three species tested, as far as the relation of slope of grain to these strength properties is concerned.

From these tests it is evident that compressive strength is but little affected until quite steep slopes of grain (1 in 10 or steeper) are reached. Modulus of elasticity is more affected and begins to show an appreciable decrease at a slope of 1 in 15. Modulus of rupture decreases even more rapidly and is appreciably deficient at a 1-in-20 slope. The most pronounced effect is on work to maximum load and maximum drop, both measures of shock resistance, which are considerably deficient, in comparison with perfectly straight-grained material, even at a slope of 1 in 25 and decrease very rapidly as slope of grain increases.[32]

Wood-Inhabiting Fungi

Wood is subject to attack by many low forms of plants known as fungi. These *wood-inhabiting fungi* differ from ordinary green plants in form, lack of green coloring matter, and methods of nutrition. Unlike green plants, they are unable to manufacture their own food, but must have organic material already prepared for their use. This they find in the products stored in the cells of the wood in which they are growing or in the actual wood substance composing the cell walls.

---

[30] Newlin and Johnson, footnote 20.

[31] T. R. C. Wilson, The effect of spiral grain on the strength of wood, *Jour. For.*, Washington, Vol. 19, Nov. 1921, pp. 740–7.

[32] For approximate reductions in the strength of beams and columns with different slopes of grain, see Table 19.

TABLE 8. EFFECT OF CROSS GRAIN ON STRENGTH OF WOOD*

AVERAGE PERCENTAGE DEFICIENCY IN STRENGTH PROPERTIES OF SPIRAL- AND DIAGONAL-GRAINED MATERIAL OF VARIOUS SLOPES WITH RESPECT TO STRAIGHT-GRAINED MATERIAL

	Static Bending				
Slope of Grain	Modulus of Rupture	Modulus of Elasticity	Work to Maximum Load	Impact Bending Maximum Drop	Compression Parallel to Grain Maximum Crushing Strength
White ash					
1:25	4	2	9	6	0
1:20	6	3	17	12	0
1:15	11	4	27	22	0
1:10	18	7	43	37	1
1:5	36	22	61	59	7
Sitka spruce					
1:25	2	2	14	8	
1:20	4	4	21	13	
1:15	8	7	33	22	
1:10	17	13	55	45	
1:5	44	36	76	69	
Douglas fir					
1:25	7	4	17	1	
1:20	10	6	24	4	
1:15	15	8	34	13	
1:10	25	14	46	31	
1:5	54	40	68	65	
Average for three species					
1:25	4	3	13	5	
1:20	7	4	21	10	
1:15	11	6	31	19	
1:10	19	11	48	38	
1:5	45	33	68	64	

* From T. R. C. Wilson, The effect of spiral grain on the strength of wood, *Jour. For.*, Washington, Vol. 19, Nov. 1921, p. 747.

Two groups of wood-inhabiting fungi are recognized, according to their activities in the wood. Chief of these is the group of **wood-destroying fungi,** whose activities result in the chemical disintegration of the actual wood substance and give rise to the condition known as **decay**[33] (also termed rot, dote, doze, or punky wood). From the point of view of their effect on the strength of wood, the fungi in this group are particularly important.

The second group of wood-inhabiting fungi comprises those that are not actively engaged in the disintegration of the wood substance but feed chiefly on the easily digested organic compounds stored in the cell cavities. They accordingly have little if any effect on the strength of the infected wood. This second group of fungi may itself be further subdivided into (1) the **wood-staining fungi,** which penetrate the wood, at least to some extent, and discolor the material, and (2) the true **molds,** which grow superficially on lumber and other products and rarely discolor it.

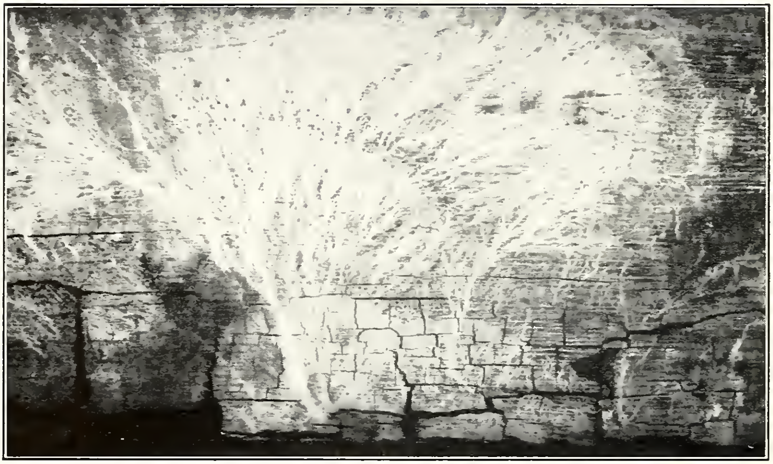
DECAY

Some species of wood-destroying fungi attack living trees, seriously weakening them, or making them hollow, or, in the case of "pecky" cypress and incense cedar, filling the wood with galleries like those of boring insects. A much larger variety work only in felled timber or in rough or manufactured products, such as poles, posts, cross ties, and sawed lumber and timbers. In all cases, however, the method of destruction is the same.

That portion of the fungus plant working within the wood consists of microscopic, usually branched mycelial threads, or hyphae, which are invisible to the unaided eye unless they occur *en masse.* These hyphae form the absorbing system of the fungus and in function are somewhat comparable to the roots of ordinary green plants. Two principal vegetative stages are recognized in the development and activity of a decay-producing fungus in the wood, the *incipient stage* and the *advanced* or *typical stage.* In the former the hyphae ramify and penetrate the wood, passing from cell to cell through the natural openings (pits) or, more often, ignoring the pits and boring through the cell walls at random, often passing through a large number of cells in a direct line. In this incipient stage there is little or no evident breaking down of the structure of the wood, but the infected material commonly exhibits slight color changes. In the advanced or typical stage the disintegration of the wood is readily recognized by virtue of pronounced discolorations and changes in its continuity and texture, the wood becoming punky, soft and spongy, stringy, ringshaked, pitted, or crumbly, depending on the nature of the attacking fungus and the extent of its work[34] (see Fig. 26).

---

[33] Although bacteria are frequently credited with causing decay, it is now generally recognized that their ability to attack sound wood is negligible under natural conditions, although they may have a secondary effect working in conjunction with the fungi after decay has started



U. S. Forest Service Photo

FIG. 26. Advanced decay in oak, showing fan-shaped mycelial mats and the characteristic cracking of wood typical of certain brown rots.

The reproduction of a fungus is commonly carried on by means of microscopic spores, which are comparable in function to the seeds of higher plants. These spores are borne in vast numbers in or on definite fruiting bodies (conks, brackets, toadstools, leathery incrustations, and so on), that develop on the surface of infected wood in the advanced stages of decay. The spores are blown about by the wind and, when conditions for germination and subsequent development are favorable, are capable of infecting sound wood on which they may fall. The spread of the fungous infection may also be carried on, without the formation of spores, by the direct growth of hyphae from infected wood to sound material in contact with it. In a moist atmosphere the fungi may even spread over other materials for some distance to reach sound wood. Decay is often spread in this way in the concealed portions of buildings, in lumber yards, and in other situations when conditions are favorable.

---

[34] For more detailed discussion of the processes of decay see Ernest E. Hubert, The diagnosis of decay in wood, *Jour. Agr. Res.*, Washington, Vol. 29, Dec. 1, 1924, pp. 523–67.

Requirements for Decay

The conditions necessary for the growth and development of decay-producing fungi are four-fold: (1) an adequate supply of suitable food, (2) a sufficient amount of moisture, (3) at least a small amount of air, and (4) a favorable temperature.

The food required for the nourishment of a wood-destroying fungus is supplied chiefly by the wood substance (cell walls) of the host, although the starches, sugars, and other materials stored in the cell cavities may also be drawn on. The wood substance itself—a highly complex combination of cellulose and lignin—is not suitable for the use of the fungus in its natural combined state, but by the secretion of certain ferments, or "enzymes," the hyphae are able to split it up into its component cellulose and lignin complexes, either or both of which can then be assimilated. Some fungi (*white rots*) absorb the ligneous matter in their further disintegration of the wood and leave almost pure cellulose, which is white; others (*brown rots*) remove the cellulose and leave a brittle, brownish mass of lignin compounds; still others absorb both compounds in varying amounts. The particular reactions produced in wood by the various fungi serve as a basis for the classification of decays.[35]

There is a great dissimilarity in the *durability* of different woods, or the natural resistance they offer to decay, and even the same species will show marked variation under different conditions of exposure. The factors responsible for the differences in durability are numerous and varied, some of them having to do with conditions within the wood itself, the others with circumstances attending its use. The sapwood of all woods is readily susceptible to decay, whereas in many species the heartwood is relatively resistant to such deterioration. This is particularly true in woods that possess deeply colored heartwood, such as black locust, black walnut, redwood, and eastern red cedar, although some of the light-colored cedars are also extremely durable. On the other hand, the heartwood of such woods as spruce, hemlock, aspen, hickory, maple, willow, and tupelo shows little increase in durability over the sapwood.

---

[35] For classification of wood rots see Hubert, footnote 34; also Ivory, White, and Upson, footnote 4, pp. 60–1. Descriptions of decays in woods used in aircraft are given in J. S. Boyce, *Decays and discolorations in airplane woods,* U. S. Dept. Agr. Bul. 1128, Washington, 1923, and in *The significance of the discolorations in aircraft veneers,* For. Prod. Lab. Repts. 1375–9, Madison, 1942–43.

The greater durability of the heartwood over the sapwood, in those woods in which such a distinction is present, is attributed to certain chemical and physical changes that take place when and after the sapwood changes to heartwood and usually result in the darkening of the wood. The exact nature of these alterations is not thoroughly understood, but they apparently involve the deposition in the cells of the heartwood of certain materials (gums, resins, tannins, or essential oils) resulting from the process of death and increased possibly by oxidation and other chemical changes. These extraneous substances, being more or less toxic to the wood-destroying fungi, tend to retard or inhibit their growth in the wood.[36] A similar effect is produced when wood is treated with creosote, zinc chloride, pentachlorophenol, or other toxic wood preservatives that serve to poison the food supply of the fungi.

The development of decay is dependent on the presence of a rather appreciable amount of moisture in the wood. Although the minimum requirements vary with the different fungi, it is generally considered that wood must contain over 20 percent moisture before it will rot. Consequently, thoroughly air-dried or kiln-dried material is immune from decay unless subjected to wetting or dampness for a period sufficient to raise its moisture content to approximately the fiber-saturation point. Moreover, if wood in which decay is already established is dried to a moisture content below the minimum required by the particular fungus, the further development of the rot will be checked. However, the fungus may merely remain dormant until suitable moisture conditions are restored, and its development may therefore be intermittent.[37]

---

[36] For further discussion of the natural durability of wood see George M. Hunt and George A. Garratt, *Wood preservation,* McGraw-Hill Book Co., New York, 1938, pp. 39–45. See also *Wood handbook,* rev., U. S. Dept. Agr. Unnumbered Publ., Washington, 1940, pp. 41–3.

An exception to the afore-mentioned moisture requirement is sometimes claimed for the so-called *dry-rot* fungi, which are commonly found in comparatively dry situations in factory and house timbers and, consequently, are popularly believed to require little or no moisture for their development. Actually the term dry rot is a misnomer as all fungi are powerless to infect thoroughly dry timber or to spread through the wood unless adequate moisture is available. Once their development has begun in the moist wood, however, these fungi are able to spread for a considerable distance in the dry portions of the timbers, maintaining themselves by conducting the water for their needs from the moist areas to the drier sections through porous, root-like strands.[38] Dry rot is particularly to be dreaded because it works unseen within the walls, floors, casings, and other hidden portions of buildings, and its presence is often unknown until some portion of the building collapses. It is active in nearly every region of the United States, working more commonly in softwoods than in hardwoods.

Decay is normally anticipated and found in parts of buildings and other forms of construction that are directly in contact with the ground or in locations where moisture collects and cannot readily evaporate. The ground line of posts and poles, the base of porch columns, sills on or near the ground, the ends of beams built into concrete or masonry piers or into exterior walls, and the lowest steps of porches are among the locations where decay normally starts. In such situations the length of service of the wood is discounted, or protective measures, such as creosoting or treatment with other preservatives, are applied. In addition extensive damage is sometimes done to interior building construction, where for various reasons the moisture content of the wood in certain parts of a structure is abnormally high. This is particularly the case in textile and paper mills and canning factories, in which a high atmospheric humidity is maintained. Since wood tends to come into equilibrium with the moisture in the surrounding air, fairly dry timbers exposed to such atmospheric conditions absorb considerable quantities of water and are consequently subject to decay. This condition is especially serious in the roof timbers of such buildings, particularly during cold weather, when the wood is cooled from the outside, causing the moisture in the air within the building to condense in contact with the timbers. For the same reason, local decay in buildings is sometimes started near cold-water pipes which "sweat," owing to the condensation of the moisture in the air in contact with them.

---

[37] For data as to the length of time certain fungi remain alive but inactive in wood stored in the air-dry conditions of a room see Ernest E. Hubert, *Effect of kiln drying, steaming, and air seasoning on certain fungi in wood,* U. S. Dept. Agr. Dept. Bul. 1262, Washington, 1924, pp. 15–16.

[38] C. J. Humphrey and L. E. Miles, *Dry-rot in buildings and stored construction materials and how to combat it,* Ala. Poly. Inst. Extension Serv. Circ. 78, Auburn, 1925.

In other instances failure of wood through decay has been noted when poorly seasoned material, or timber that has been exposed for protracted periods to damp weather and fungous infection, is used without provision for adequate ventilation about it. Beams, posts, girders, and the like, used in an unseasoned condition and enclosed by metal, masonry, or other covering that prevents the drying out of the timbers, may afford an ideal condition for decay. In such cases, decay commonly progresses undetected, and serious and unexpected loss may occur.

A supply of air is necessary for fungous development, but the demands in this respect are moderate, and under ordinary conditions the amount within and surrounding wood in service or in storage is ample. Even the interior of trees and large unseasoned timbers usually contains enough air in the cells to permit the growth of fungi, when other conditions are favorable. There may be a definite relationship between the air supply and water supply of wood and its susceptibility to decay, since wood that is thoroughly saturated with water is devoid of air and consequently will last indefinitely. Such is the case with water-logged pieces. On the other hand, as has been previously observed, the amount of air in the wood may be so great that the supply of moisture is reduced below the required minimum.

Although wood-destroying fungi are capable of development over fairly wide ranges of temperature, their best growth takes place within comparatively narrow limits. These optimum temperatures vary with the individual species, but most of the fungi thrive around 80°F. Below the optimum for its development the growth of a fungus is retarded, and at low temperatures the plant becomes dormant, although no degree of cold such as occurs naturally will kill either the mycelium (hyphae) or spores. On the other hand, an increase in temperature of but a few degrees above the optimum has a far greater retarding effect; a rise of 4 to 8 degrees above this point often resulting in complete cessation of growth, or even death, as in the case of *Merulius lachrymans* (one of the dry-rot fungi), which is very sensitive to increases in temperature.[39] Hubert demonstrated that "the temperature of commercial kiln runs, excepting temperatures below 120°F., are effective in sterilizing infected wood up to and including 4 by 4 inches square. Pieces 6 by 6 inches and 8 by 8 inches square were sterilized by treatment at 130°F. for 9 hours at saturated atmosphere and by steam-pressure treatment."[40]

Wood-Staining Fungi

There are a number of wood-inhabiting fungi that penetrate the wood and discolor it, and, since practically all of them confine their activities to the sapwood,[41] their effect is commonly spoken of as **sap stain.** Of these the *blue-stain* fungi (*Ceratostomella, Endoconidiophora, Diplodia,* and *Graphium*), common in the pines, spruces, red gum, and other species of wood, are the most troublesome. Blued stock never entirely loses its usefulness unless decay has developed, but it represents a depreciation loss as the stain detracts from the appearance of the lumber and, consequently, lowers the grade and price of the product. When the stain is more or less superficial in rough lumber, it may be removed in the planing operation, but it is commonly too deep-seated to be so easily eliminated.

All these wood-staining fungi are similar in their general development and activities. They exist principally on the starches, sugars, and the like, stored in the cell cavities, and progress from one cell to another in their search for food. In passing from cell to cell, the hyphae usually seek out the natural openings, or pits, although it is not uncommon to find that they have dissolved away portions of the cell walls to create a passage-way. It is on the less lignified ray cells, however, that any disintegrating attack of these fungi is concentrated, the walls between the ray cells often being completely broken down. The various colors, or stains, are apparently imparted to the wood by the massing of the hyphae in the material, rather than by any staining of the cell walls or by the formation of colored by-products.

---

[39] C. J. Humphrey, *Timber storage conditions in the eastern and southern states with reference to decay problems,* U. S. Dept. Agr. Bul. 510, Washington, 1917, p. 3.

[40] Hubert, footnote 37, p. 18.

[41] Exception is noted in the grayish-olive stain of hardwoods, produced by *Lasiosphaeria pezizula,* and other minor stains which frequently occur in heartwood.

In common with the other wood-inhabiting plants, staining fungi find the optimum conditions for their growth in warm, humid situations. Blue stain is particularly prevalent during the summer months in the South, and, in other sections of the United States, in mill yards where unseasoned lumber is piled for seasoning or for storage without adequate provision for ventilation between the boards. It also occurs in freshly cut logs and in unseasoned lumber in transit. Under favorable circumstances the development of sap stain is extremely rapid, and the discoloration may occur within 48 hours after the logs or boards are cut. Early removal of logs from the forest and the rapid air seasoning of lumber by open piling are logical methods of prevention. Where log ponds and dry kilns are available, entirely submerging the logs in water soon after cutting and kiln-drying the lumber directly from the saw are to be recommended. The ordinary kiln-drying process has been found to be entirely effective against blue stain. The dipping of unseasoned lumber in antiseptic solutions prior to air seasoning has been practiced for some time and is reasonably efficient. Sodium carbonate and sodium bicarbonate have been commonly used for this purpose, and, more recently, the chlorinated phenols and organic mercurials have come into prominence as stain preventives.[42]

MOLDS

True molds, similar to those that form on damp bread or cheese, thrive on the surface of wood in the presence of abundant warmth and moisture. Such conditions are present when unseasoned or partially seasoned lumber or veneer is piled without proper ventilation, so that little or no drying takes place. Carloads of unseasoned lumber frequently mold in transit, and in kiln drying stock at high humidities and at temperatures below 135°F. molds often develop to such an extent that they seriously interfere with the circulation of air through the pile. Adequate ventilation of unseasoned lumber during storage or in shipment is, of course, the most practical preventive measure. In kiln drying, the superficial growth of these fungi may be destroyed by steaming the stock at a temperature of 170°F. and 100 percent humidity for 1 hour. Although molds do not appreciably affect the strength of wood, they are objectionable from the standpoint of appearance. However, since they are mostly confined to the surface of the wood, penetrating the cells only slightly, they can usually be dressed off. On the other hand, the conditions that produce them are also conducive to the development of wood-destroying fungi; hence, the moldy wood may also be infected with decay.

---

[42] For more detailed discussion of wood-staining fungi see Theodore C. Scheffer and Ralph M. Lindgren, *Stains of sapwood and sapwood products and their control,* U. S. Dept. Agr. Tech. Bul. 714, Washington, 1940.

Also Ernest E. Hubert, *Sap stains of wood and their prevention,* U. S. Dept. Comm. Nat. Com. on Wood Utiliz., Washington, 1929.

Effect of Decay and Sap Stain on Strength

Since decay involves an actual breaking down of the cell walls, it is evident that it vitally affects the strength of wood, particularly in the advanced stage. In their final stages both brown-rot and white-rot fungi are known to effect almost complete destruction of the wood structure. Tests made in 1918 on matched pieces of Sitka spruce and Douglas fir, however, indicated that in their incipient stages the brown-rot fungi, *Polyporus schweinitzii* and *Fomes laricis,* caused a greater reduction in strength than the white-rot fungus, *Fomes pini.*[43]

A later analysis of these data and of results gathered in subsequent studies showed that, at the outer limit of infection by *Polyporus schweinitzii,* toughness was reduced by approximately 20 percent, even though the only visual indications of incipient decay are inconspicuous yellowish longitudinal streaks in the wood. A comparable reduction in toughness due to *Fomes pini* would ordinarily not occur until the decay had advanced to the stage characterized by the formation of white pockets.[44] In the words of the authors of this report: "Although there is a progressive increase of brittle appearance of the failures in passing from the sound material to that which is most decayed by *Polyporus schweinitzii* and of lowest toughness, there is little correlation between the appearance of the wood and the degree of decay or loss of toughness. However, in the case of the *Fomes pini* specimens, the extent of pocket formation definitely parallels the reduction in toughness. . . . Wood showing the incipient stage of *Fomes pini* decay, known commercially as firm red heart, will show losses in maximum crushing strength in compression parallel to grain and modulus of rupture in static bending not much greater than 10 or 15 percent and, at least when dry, no more than a 10 to 25 percent loss in impact bending up to the time the pockets are formed.

---

[43] Reginald H. Colley, The effect of incipient decay on the mechanical properties of airplane timber, Abstract, *Phytopathology,* Vol. 11, Jan. 1921, p. 45.

". . . Average reductions by *Polyporus schweinitzii* in the most severely attacked wood . . . were about 10 percent in specific gravity, 30 percent in maximum crushing strength in compression parallel to grain, and 95 percent in toughness, as compared with reductions by *Fomes pini* in the late pocket stage of about 30 percent, 70 percent, and 95 percent, respectively. . . .

"Although . . . (both organisms) cause large reductions in strength in advanced stages of their development, sound wood close to an infected area is normal in strength properties."

As indicated in the foregoing, the early, or incipient stage of decay frequently imparts a pronounced brashness, or brittleness, to the wood, with the result that the infected material tends to break suddenly under stress, with but little deformation and with a more or less smooth and unsplintered fracture. Brashness, however, may also be due to other causes and is not necessarily an indication of the presence of decay.[45] In the advanced stage the strength of wood may be virtually reduced to zero. In view of these facts, infected material should be rigidly excluded from use when strength is a consideration of any importance. The selection of timber for soundness is complicated, however, by the fact that the presence of the fungi is often hidden from casual inspection, particularly in the early stages and in material that has been weathered.

---

[44] Theodore C. Scheffer, T. R. C. Wilson, R. F. Luxford, and Carl Hartley, *The effect of certain heart rot fungi on the specific gravity and strength of Sitka spruce and Douglas-fir,* U. S. Dept. Agr. Tech. Bul. 779, Washington, 1941.

[45] See text discussion of Compression Failures and Cross Breaks, page 120; Density, page 152; Moisture Content, page 179; and Temperature, page 188.

Also C. C. Forsaith, The morphology of wood in relation to brashness, *Jour. For.*, Washington, Vol. 19, Mar. 1921, pp. 237–49. And Arthur Koehler, *Causes of brashness in wood,* U. S. Dept. Agr. Tech. Bul. 342, Washington, 1933.

Considerable work has been done from time to time to determine the effect of sap-staining fungi on the strength of wood, and a variety of results has been obtained. The results of such reliable tests as have been made, however, indicate that these fungi have a slight weakening effect on the wood, but do not usually decrease its strength sufficiently to unfit it for ordinary commercial use.[46]

In a series of controlled staining experiments, thoroughly stained specimens of southern pine sapwood were tested in specific gravity, compression parallel to grain, static bending, and toughness.[47] Toughness and work to maximum load in static bending (both regarded as indices of shock resistance) were the only properties affected to a marked degree. The greatest reduction in toughness was 75 percent; the least about 9 percent. The greatest loss observed in specific gravity in these tests was 3.8 percent. It must be borne in mind, however, that the conditions resulting in the development of sap stain are also favorable to decay, and the two types of fungi may occur together. Consequently, stained wood should be examined thoroughly before being used for purposes having exacting strength requirements.

Decay and sap stain have also been determined to have pronounced effects on other properties of wood. Decay apparently brings about excessive shrinkage in wood and may consequently be instrumental in producing checks; it is also credited with causing the collapse of wood during kiln drying.[48]

---

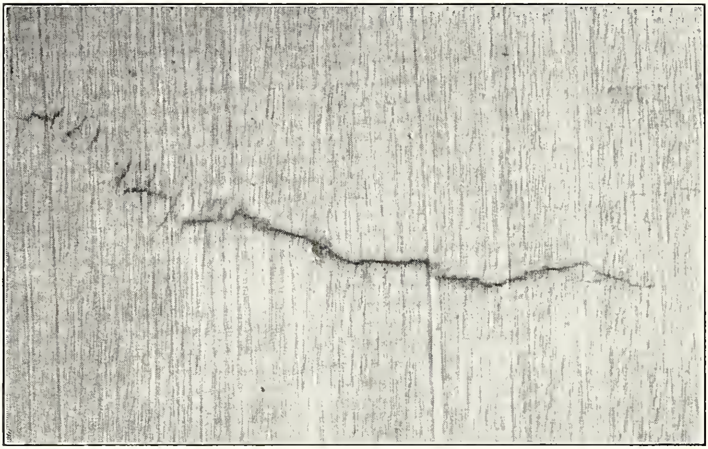
[46] Scheffer and Lindgren, footnote 42, pp. 28–30.

[47] A. Dale Chapman and Theodore C. Scheffer, Effect of blue stain on specific gravity and strength of southern pine, *Jour. Agr. Res.*, Washington, Vol. 61, July 15, 1940, pp. 125–33.

[48] Additional information concerning the influence of decay and stain on the properties of wood is given in George M. Hunt and George A. Garratt, *Wood preservation,* McGraw-Hill Book Co., New York, 1938, pp. 37–9. Also J. S. Boyce, *Forest pathology,* McGraw-Hill Book Co., New York, 1938, pp. 376–7.

Compression Failures and Cross Breaks

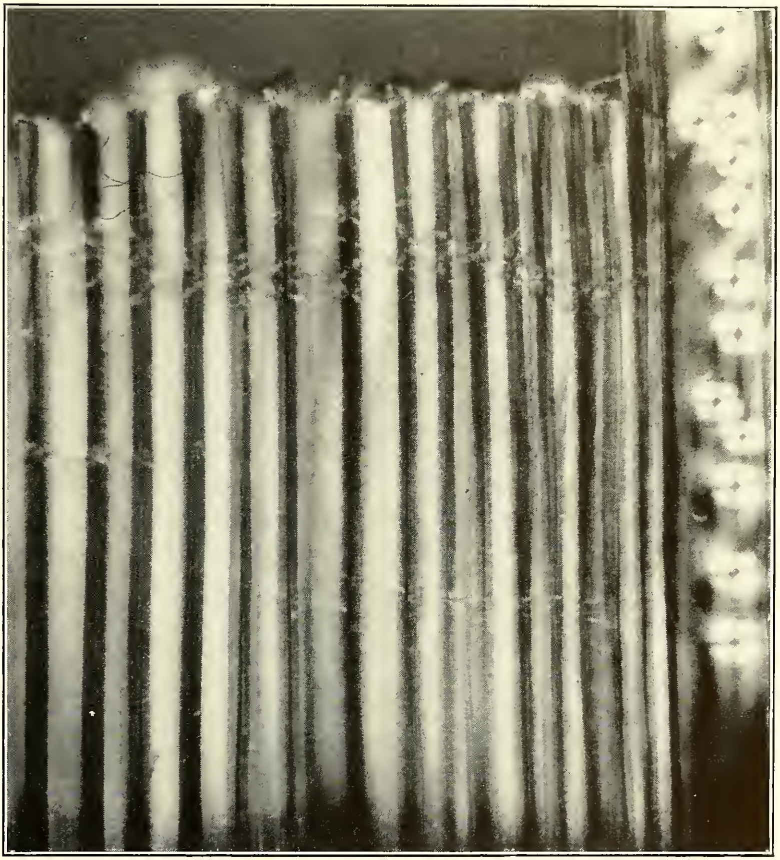
Compression failures are localized wrinkles or creases in wood, produced by the endwise compression of the fibers well beyond the proportional limit. They extend across the fibers more or less at right angles to the direction of the grain and, in extreme cases, may be visible on the exposed surface of the wood as fairly pronounced ridges, showing the crumpling or buckling of the cells to advantage (see Fig. 27). More often, however, they appear as fine whitish lines or streaks and are frequently indiscernible to the unaided eye. Even though difficult to distinguish superficially, compression failures are associated with an overstressed condition of wood, and zones of slip planes, indicative of initial failure, are evident under the microscope (Fig. 28).



Yale Photo

FIG. 27. Compression failure in African mahogany (*Khaya*).

Compression failures may result from abnormal stresses set up in the standing tree by the bending of the bole during severe wind storms. Under such a condition, the windward side of the bole is in tension and the leeward side in compression. Since unseasoned wood subjected to bending normally fails first in compression, it is apparent that compression failures may result in the wood on the leeward side of exposed trees, without further damage to the trunks. It is probable, however, that a more common cause of such failures is to be found in the severe impact stress developed when trees are felled across logs, rocks, or other objects. These defects may also result at times from rough handling in transportation or manufacture or may occur when wood is unduly stressed in use.[49]



Forest Products Laboratory Photo

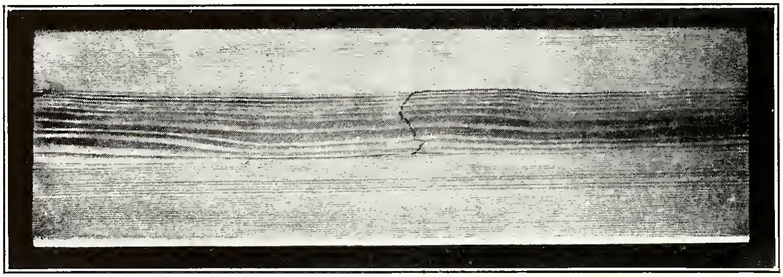
Fig. 28. Photomicrograph of compression failures in Sitka spruce showing zones of slip planes in the cell walls. Taken with polarized light. ×280.

---

[49] For further information on the detection of compression failures, see Forest Products Laboratory, *Wood aircraft inspection and fabrication,* ANC Bul. 19, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1943.

Cross breaks, which resemble compression failures in general appearance, are tension failures and represent separations of the wood cells across the grain. They are usually caused by restraint of local abnormal shrinkage, such as characterizes *compression wood* (see Fig. 29), but may also result from external forces.

Compression failures and cross breaks seriously impair some of the strength properties of wood. This is notably the case with shock-resisting ability, and timbers containing even microscopic failures may break suddenly along the plane of injury when subjected to relatively low impact stresses, producing what is known as a brash or brittle failure. The static-bending strength of wood is less seriously affected. Such defects are most serious, of course, when located on the tension side of a beam. In compression parallel to the grain these failures do not appreciably affect the strength of wood.[50]



Forest Products Laboratory Photo

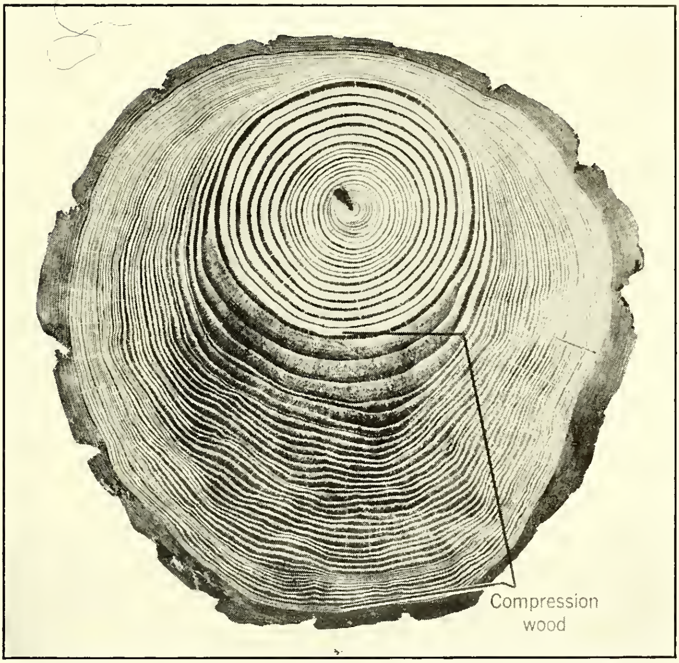
FIG. 29. Cross break in compression wood. The restraint of abnormal longitudinal shrinkage in the compression wood (darker zone) set up tensile stresses sufficiently great to rupture the wood.

Compression Wood

Compression wood (also known as *redwood*) is formed on the under side of branches and on the lower side of leaning trunks of coniferous trees. This type of wood is considerably heavier than the normal wood and has much wider growth rings. It is further distinguished, in such woods as southern pine and Douglas fir, by a lack of contrast between springwood and summerwood and a relatively dark color (see Fig. 30). Compression wood is undesirable because it is characterized by a pronounced tendency to warp, marked longitudinal shrinkage (see Fig. 29), and relatively low stiffness, bending strength, and toughness for its weight. In bending, the ratio of tensile to compressive strength is low, a condition which leads to characteristic brash failures. Tests made at the Forest Products Laboratory in static bending, compression parallel to grain, tension parallel to grain, and toughness, on both normal wood and compression wood of several coniferous species, showed that, when tested green, compression wood was deficient to normal wood only in modulus of elasticity and tension parallel to grain. Its specific gravity, however, ranged from 13 to 39 percent greater than that of normal wood, and, when adjusted for differences in specific gravity, compression wood was lower than normal wood in all properties except work to maximum

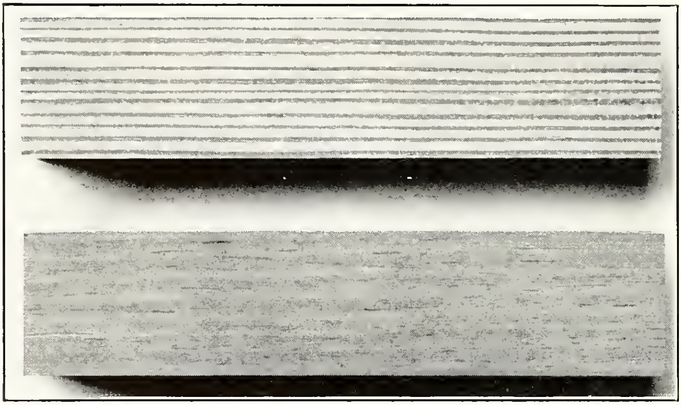
---

[50] L. J. Markwardt, Compression failures as defects, *Hardwood Record,* Chicago, Vol. 39, Oct. 25, 1914, pp. 24–5.



Forest Products Laboratory Photo

Fig. 30*A*. Cross section of southern pine log showing compression wood load and total work in static bending. After adjustment for differences in specific gravity, modulus of elasticity ranged from 43 to 61 percent of normal, modulus of rupture from 67 to 90 percent, and toughness from 37 to 83 percent. Relative values for compression wood are usually somewhat lower when comparison is made in the air-dry condition.[51]



Forest Products Laboratory Photo

Fig. 30*B*. Radial surface of loblolly pine showing normal wood (upper) and compression wood (lower). Note lack of contrast between springwood and summerwood in compression wood.

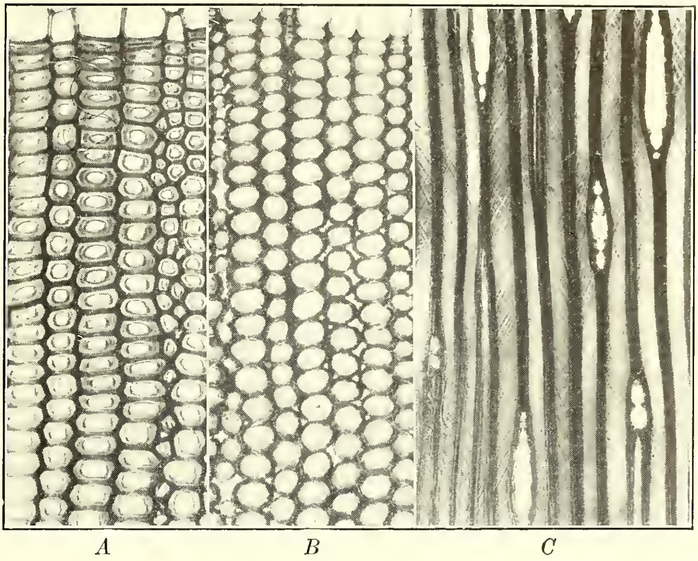
Microscopically, compression wood is characterized on the cross section by rounded rather than normally angular summerwood tracheids (Fig. 31*A* and *B*), with conspicuous intercellular spaces. On a longitudinal section compression wood is characterized by a large angular deviation of the fibrils of the cell wall from the longitudinal axis of the tracheids (Fig. 31*C*). Orientation of the fibrils is indicated in the photomicrograph by the direction of checks in the cell walls.

The exclusion of this abnormal wood in dense Douglas fir and southern pine is provided in the selection of structural material of American Lumber Standards by the stipulation that the contrast in color between summerwood and springwood must be distinct and the summerwood must be dark. The cause of the production of compression wood is not definitely known, being variously attributed to wind action, longitudinal compressive stresses, nutrition, and gravity.[52]

---

[51] M. Y. Pillow and R. F. Luxford, *Structure, occurrence, and properties of compression wood,* U. S. Dept. Agr. Tech. Bul. 546, Washington, 1937.

See also G. E. Heck, "Compression" wood and failure of factory roof beam, *Eng. News-Record,* New York, Vol. 83, Sept. 11, 1919, pp. 3–8.



Forest Products Laboratory Photo

FIG. 31. Photomicrographs showing normal wood and compression wood cells in Douglas fir summerwood. *A*. Transverse section of normal wood. *B*. Transverse section of compression wood showing rounded cross-sectional shape of cells and intercellular spaces. *C*. Longitudinal section of compression wood with prominent spiral checks and striations in the secondary cell walls. ×140.

Pitch Pockets and Pitch

Pitch, or resin as it is more properly known, is most abundantly developed in the wood of the pines, spruces, larches, and Douglas fir, where it is chiefly associated with normal *resin ducts*.[53] In addition to these normal resin canals, traumatic ducts often develop as a result of injury, not only in these woods, but in hemlock and true fir (*Abies*) as well. In the longleaf and slash pines, the resin produced in these traumatic resin ducts, formed as a result of the chipping of the outer layers of sapwood, or, more recently, by chemical stimulation of exposed sapwood, is the source of much of our turpentine and rosin.

---

[52] George P. Burns, *Eccentric growth and the formation of redwood in the main stem of conifers*, Vt. Agr. Expt. Sta. Bul. 219, Burlington, 1920.

Also M. Y. Pillow, Compression wood cause of bowing and twisting, *Wood Working Industries*, Jamestown, N. Y., Vol. 8, Nov. 1930, pp. 26–7.

And Raymond Kienholz, The wood structure of a "pistol-butted" mountain hemlock, *Am. Jour. Bot.*, Lancaster, Pa., Vol. 17, Oct. 1930, pp. 739–64.

[53] Resin ducts are long, narrow, intercellular channels in the wood limited by specialized parenchyma cells which are capable of producing resin. They extend both with the grain and at right angles to it; in the latter case they are formed within the rays.

Not infrequently, in response to various stimuli, pitch or resin accumulates in the wood outside of the resin ducts. In such cases it either permeates the wood cells in patches or streaks of varying size or is massed in definite openings or splits in the wood.

PITCH POCKETS

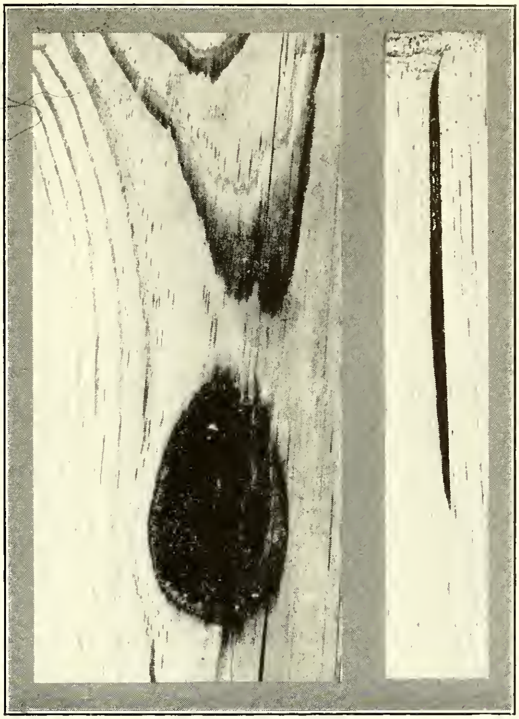
Pitch pockets are well-defined openings between the annual rings of growth, usually containing, or having contained, more or less pitch (or resin), in either solid or liquid form (see Fig. 32). Bark may also be included in these openings, in which case they may resemble typical **bark pockets.**[54] Pitch pockets are somewhat lens-shaped, being curved on the side toward the periphery of the tree, and range from less than 1/8 inch to about 2 inches in width and from 2 to 8 inches, or more, in length. They affect only one or two growth rings, as a rule, and are hidden until exposed by the saw, rendering it impossible to cut the lumber with reference to their position. Often several boards are damaged by a single pocket. These defects are frequently encountered in larch, spruce, Douglas fir, and pine, especially longleaf and other hard pines. Forsaith[55] also mentions their occurrence in species like true fir (*Abies*) in which traumatic resin ducts are formed as a result of wounding.

The exact causes of pitch pockets have not been fully established. Since they are apparently confined to woods possessing normal or traumatic resin ducts, it is frequently assumed that pitch pockets bear a causal relation to resin ducts. One theory, that of H. Mayr,[56] holds that these defects are formed as a result of the exudation of resin from the horizontal resin ducts into the growing cambial layer. This resin kills the surrounding cells, causing them to collapse and form pockets, in which the resin is isolated by a subsequent growth of parenchyma cells. The exudation of the resin is due, according to this theory, to the pressure exerted on it by the turgid sapwood. Mayr further contends that, because of differences in the turgidity of the wood in the

---

[54] Bark pockets are small, pitch-free patches of bark which have been wholly or partially included in the wood, apparently as the result of the healing over of areas of dead cambium. They are of more general occurrence than pitch pockets, not being confined to those woods that possess normal resin ducts. They are similar in effect to pitch pockets, since both defects represent actual breaks in the continuity of the wood and are characterized by a localized distortion of the grain on the side nearest the cambium.

[55] C. C. Forsaith, *The technology of New York State timbers,* N. Y. State Col. For. Tech. Publ. 18, Syracuse, 1926, p. 263.



Forest Products Laboratory Photo

Fig. 32. Pitch pockets exposed on tangential (left) and radial (right) surfaces.

---

[56] Heinrich Mayr, *Das Harz der Nadelhölzer,* Julius Springer, Berlin, 1894, pp. 38–40. See J. R. Watkins, Pitch pockets and their relation to the inspection of airplane parts, *Jour. Franklin Inst.,* Philadelphia, Vol. 188, 1919, pp. 245–53.

vicinity of branches from the main trunk, pitch pockets are most frequently found at these points. He also states that these defects are more frequent in trees growing alone and subjected to extremes of temperature and humidity than in those within the forest. Forsaith[57] likens a pitch pocket to an enormous resin canal since its cavity is surrounded by epithelial tissue. Its localization to a definite portion of the growth ring indicates that a pitch pocket is formed as a result of activity of the cambium in which contiguous cambial derivatives abruptly cease differentiating as tracheids to develop resin epithelial tissue. After the formation of several rows of such cells, the meristem suddenly resumes the normal development of tracheids. The cavity of the pitch pocket, like that of a resin canal, is produced as a result of the separation of the resin-forming epithelium, and consequently is postcambial in its development. Another theory is that the resin exudes from the tree following external injury and is subsequently closed over by later growth. Snyder[58] cites the effect of certain insects, particularly bark beetles, in causing pitch pockets in this way.

The effect of pitch pockets on the strength of wood depends primarily on their abundance, size, and position in the piece. Since they represent actual breaks in the continuity of the wood, these defects are comparable in effect to small shakes, although the localized distortion or dip of the grain on the convex side of the pocket may tend to increase the slope of the grain and thus accentuate the weakening effect of the pockets.[59] Thus, pitch pockets near or at the neutral plane of wooden members subjected to bending tend to reduce the area acting in resistance to horizontal shear, although they are seldom large enough to cause shear failure directly, whereas those defects exposed near the middle of the upper or lower surface may produce local cross grain and thus weaken the wood in resistance to compression or tension. During the early part of World War I, the presence of pitch pockets caused a heavy rejection of wing beams and other airplane parts. Later, tests made at the Forest Products Laboratory led to the conclusion that the reduction in strength due to these defects had been overrated, and specifications for spruce and Douglas fir wing beams were revised.

---

[57] Forsaith, footnote 55, pp. 263–4.

[58] Thomas E. Snyder, *Defects in timber caused by insects,* U. S. Dept. Agr. Dept. Bul. 1490, Washington, 1927, pp. 37–8.

[59] Pitch pockets are not to be confused with **pitch seams,** which are actual shakes or checks that have become filled with pitch or resin.

Limitations placed on pitch pockets in aircraft spars of solid wood are recommended for use where strength requirements are exacting:[60] "A pitch or bark pocket should be not deeper than ⅛ the width of the spar; not wider than ¼ inch or ⅛ width of spar, whichever is the less; and not longer than 2 inches or four times its distance from a corner of the spar, whichever is the less.

"The distance between two pockets . . . in the same growth layer . . . should be not less than six times the length of the longer pocket."

Pitch and Pitch Streaks

Accumulations of resin or pitch also permeate the wood cells, taking the form of poorly defined and more or less irregular patches, or of definite, often regular streaks in the wood. The term **pitch** is applied to the former condition, whereas the latter defects are known as **pitch streaks** (see Fig. 24). Like pitch pockets, these accumulations are generally confined to the four genera of conifers having normal resin ducts. They frequently result when resin formation is stimulated by injury to the tree, as when trees are "bled" for turpentine or seriously attacked by insects; in other instances their cause is not clearly understood. The chief effect of pronounced pitch or pitch streaks is to lower the grade of finishing lumber, since such defects detract from the appearance of finished material and may seriously affect its paintability. According to Snyder,[61] ponderosa and other pine trees are sometimes so pitch-soaked, as the result of attack by the larvae of the Zimmerman pine moth, that the lumber produced from them is seriously degraded and even rendered unfit for use except in the rough. Likewise the butt logs of turpentined southern pine trees may be permeated with resin for a depth of ½ to 1½ inches back from the chipped faces. However, in many cases, these highly resinous areas are removed as slabs in sawing up the logs, and the quality of lumber obtained is not affected. The normal resin content of the pines and other

[60] *Wood aircraft inspection and fabrication*, footnote 49, p. 130.

[61] Snyder, footnote 58.

resinous conifers varies considerably in the different parts of the tree. The sapwood is comparatively nonresinous, whereas the heartwood may contain high concentrations, particularly in the stump and butt logs. There may also be an abundant development of resin in the upper parts of the tree, especially where the limbs join the trunk.

For practical purposes resin (or pitch) is not considered to have any material effect on the strength of wood, although timbers in which the whole end is saturated with resin have proved somewhat erratic under test and should be regarded with suspicion.[62] One series of tests made on longleaf pine[63] indicated that very resinous specimens became increasingly stronger than similar normal pieces of the same wood, as the material was dried below the thoroughly air-dry condition. Other experiments on the southern yellow pines indicated that the endwise compressive strength, bending strength, and shock resistance of these woods are somewhat increased by the presence of resin. The compressive strength is most affected. However, the proportionate increase for a large amount of resin was found to be much less than for a moderate amount. It has been further shown that the strength of these woods is not increased as much by the presence of resin as it would be by an equal additional weight of wood substance. In this connection, it should be borne in mind that a high resin content is frequently associated with injuries, which themselves may greatly reduce the strength of wood.

The "bleeding" of southern pine trees in the turpentining operation is sometimes considered to lower the strength of the wood, but this is not borne out by investigation. Comparative tests on wood from bled and unbled trees[64] led to the conclusions: (1) that bled timber is as strong as unbled if of the same weight, (2) that the weight and shrinkage of wood is not affected by bleeding, and (3) that bled trees contain practically neither more nor less resin than unbled trees.

---

[62] J. A. Newlin and R. P. A. Johnson, *Basic grading rules and working stresses for structural timbers*, U. S. Dept. Agr. Dept. Circ. 295, Washington, 1923, p. 8.

[63] H. D. Tiemann, *Effect of moisture upon the strength and stiffness of wood,* U. S. Dept. Agr. For. Serv. Bul. 70, Washington, 1906, p. 92 and diagram, p. 70.

[64] J. B. Johnson and F. Roth, *Southern pine—mechanical and physical properties,* U. S. Dept. Agr. For. Serv. Circ. 12, Washington, 1896, p. 16.

Miscellaneous Seasoning Defects[65]

Although checking is the most common form of deterioration resulting during the seasoning of wood and the most important from the point of view of effect on the strength of structural timber, it is by no means the only defect that develops. Warping, casehardening, honeycombing, and collapse may also occur under certain conditions.

Warping, by which is meant any deviation of a piece from a true or plane surface, is of frequent occurrence in lumber. Several forms are recognized, namely, bow, crook, twist, and cup. *Bow* is a deviation of the wide face from a straight line drawn from end to end of a piece. It is usually produced by careless sawing or by differences in the longitudinal shrinkage of the two faces of a board but may also be caused by internal stresses present in the log at the time of sawing. *Crook* is a deviation of the edge from a straight line drawn from end to end of a piece, such as results from careless edging of a board. *Twist* is a deviation of a piece such that the four corners are no longer in the same plane. It is common in woods with irregular cross grain but may also occur in straight-grained woods as the result of uneven drying or internal stresses present in the wood before the tree was felled. *Cup* is a curve in a piece across the grain or width. In this last form of warping the edges remain parallel, frequently giving the board a trough-like appearance.

Cupping may occur in plain-sawed lumber, which is dried without being weighted down, since the surface originally closer to the center of the log is more nearly radial than the other and consequently tends to shrink less across the width of the board than does the other face. It also results, in both plain- and quarter-sawed material, when one side of a board dries and shrinks more rapidly than the other. Change of shape from this latter cause alone, however, is usually temporary, and the piece tends to straighten out as the drying proceeds. Cupping may also occur in boards resawed from casehardened lumber, as is explained in the following paragraphs.

---

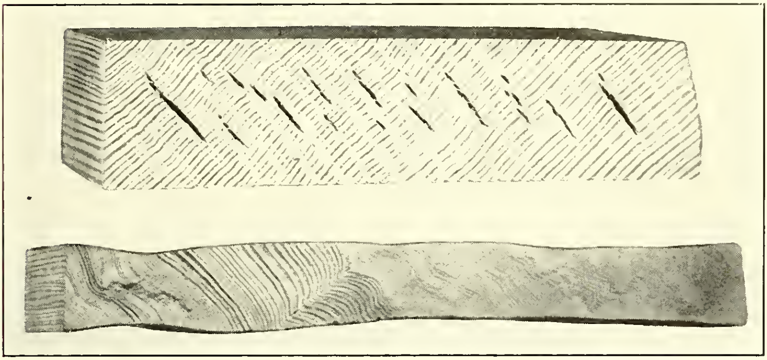
[65] More detailed discussion of seasoning defects may be found in Arthur Koehler and Rolf Thelen, *The kiln drying of lumber,* McGraw-Hill Book Co., New York, 1926.

The various forms of warping may be largely prevented by proper piling of the lumber during seasoning. They are usually objectionable for other reasons than their effect on the strength of wood, although pronounced warping may markedly reduce the bearing area of joists and other forms of lumber and prevent its satisfactory nailing in construction.

Casehardening results from the too rapid surface drying of wood. It is usually more pronounced in kiln-dried stock, but may occur during air seasoning as well. When the drying conditions are such that moisture is evaporated from the surface of a piece much more rapidly than it can be supplied from the interior by transfusion, the outer layers will reach the fiber-saturation point and begin to shrink while the inside is relatively wet and still at its greatest volume. The contraction of the exterior is thus opposed by the unchanging interior, with the result that the outside tends to become stretched; tensile stresses are accordingly set up in the outer layers, and the interior is subjected to compression. As rapid drying proceeds, these stresses become more pronounced, and the exterior either checks or reaches its final moisture content and becomes "set" without normal shrinkage having taken place. This is known as the *first stage of casehardening.* If a board in this condition is resawed, the two pieces will curve, or cup, away from each other; later, however, as the freshly exposed surfaces dry and shrink, the pieces will gradually straighten out and then cup toward each other. As drying is continued beyond the first stage, the interior gradually loses its moisture and tends to shrink away from the "set" exterior. As a result, when the wood is uniformly dry, the stresses are reversed, the inner part being under tension and the outside in compression. This is the *final stage in casehardening,* and boards resawed from lumber in this condition will permanently cup toward each other.

The stresses set up in casehardened wood have some weakening tendency, although the loss in strength is usually not serious unless it is accompanied by checking or honeycombing, which is described in the following paragraph.

Honeycombing is the term applied to the internal checking of lumber which sometimes occurs in the final stage of casehardening. If, as the interior of casehardened wood tends to shrink away from the exterior, the tensile stresses that are developed exceed the cohesion of the elements in the wood, checks or cracks develop within the piece. These checks occur along the rays, for the reasons already mentioned in the discussion of exterior checking but are normally confined within the interior layers of the wood and hence are not apparent on the surface (see Fig. 33). Honeycombing may seriously reduce the resistance of wood to longitudinal shear.



U. S. Forest Service Photo

FIG. 33. Cross sections of honeycombed Douglas fir plank (top) and collapsed redwood board (bottom).

Collapse is a defect that sometimes develops when very wet heartwood of certain species, such as redwood, western red cedar, red gum, swamp oak, and cottonwood, is kiln-dried at relatively high temperatures. Material so affected has a typical irregularly shrunken or wrinkled appearance on the surface (see Fig. 33). This defect is caused by the "caving in" of the cells over more or less extensive areas within the wood, presumably as a result of the cohesive force exerted by the contained water in pulling the cell walls together as it is withdrawn from completely water-filled cells. It sometimes occurs in streaks, giving the surface of the wood a corrugated appearance. Contributory factors in producing this phenomenon are the relatively high plasticity of the wet wood at high temperatures and the inability of air to penetrate through the saturated cell walls. When air can gain entrance readily, as is usually the case in sapwood, or is already present in the cell cavities, it expands and thus relieves the tensile stress exerted by the retreating water. As mentioned under the discussion of decay, collapse may sometimes be attributed to the weakening of the cell walls of wood by the activities of wood-destroying fungi.

Insect Injuries

For the purpose of this discussion, insect injuries have been divided into two groups: (1) insect holes, resulting from the activities of wood-boring insects, and (2) minor injuries, comprising a miscellaneous group of irregularities produced in wood by injury to the cambium or other interference with the normal production of woody tissue.

Insect Holes

Damage by wood-boring insects occurs in standing trees, saw logs, unseasoned lumber and other products, and in seasoned material. Naturally much of this loss is nonpreventable, particularly as it applies to standing timber, although even there it can doubtless be reduced by suitable forest management. However, it is through the proper handling of saw logs and converted material and the application of preservatives where possible that the greatest economy can be effected.

For the most part the damage by insects is done in the larval stage, the larvae or grubs burrowing through the wood to obtain both food and shelter and producing galleries or holes that are frequently characteristic. In some instances, however, the adult forms take an active part in the destruction. This is notably true of the mature ambrosia beetles, which often penetrate the wood for considerable distances for the purpose of laying eggs and rearing their young; of the subterranean termites, whose adult "workers" are the destructive individuals; and of the adult carpenter bees or carpenter ants. It is apparent that insect holes, by breaking up the continuity of the fibers, may considerably reduce the structural strength of wood. For this reason, stock that shows evidence of attack by wood-boring insects should be used with discretion where the strength requirements are exacting, although such material will probably not be rejected for ordinary use unless the attack has been very severe. Insect holes are similar in effect to knot holes, although there is no grain distortion about them and they are usually more limited in size; consequently, their actual effect depends to a large extent on their location in a stick and the resultant stresses to which they are subjected.

Three general types of insect holes are recognized, namely, pinholes, grub holes, and powder post.[66] **Pinholes** and **grub holes** are distinguished mainly on the basis of size: The former are defined[66] as small, round, usually open holes, ranging from $\frac{1}{100}$ to $\frac{1}{4}$ inch in diameter;[67] the latter are oval, circular or irregular holes, $\frac{3}{8}$ to 1 inch in diameter, and in some cases filled with boring dust which does not fall out when the wood is jarred. Pinholes are made by either ambrosia beetles or the several timber worms (chestnut, oak, tenebrionid, and sapwood timber worms) working in the heartwood and sapwood of various hardwoods and conifers, the injury occurring in living trees and in saw logs, timbers, bolts, and piled lumber, while they are still in the unseasoned condition. Grub holes are made in the standing tree, in the saw log, or in piled unseasoned lumber or other forms of wood by a variety of insects, including the flat- and round-headed borers, Parandra borers, locust borers, pine sawyers, carpenter worms, termites, carpenter bees, and carpenter ants. They occur in both heartwood and sapwood of all kinds of timber.

Of the afore-mentioned insects, the *termites,* or "white ants," are of particular interest because of the damage they may do, not only to unseasoned material, but also to the woodwork and contents of buildings, and to poles, posts, and other forms of wood in service, especially when it is in contact with the ground. Their attack is particularly insidious, as the termites work entirely in the dark; infested wood may be completely riddled in the interior and yet appear sound to casual inspection, since the protective outer shell is left intact. These insects, about 56 species of which are native to the United States, occur in all parts of the country but are particularly destructive in the South Atlantic and Gulf States, in the Southwest, and along the Pacific coast. In many cities in the seriously infested areas revisions of the building codes have been made or are being contemplated, in order to control these pests.[68]

---

[66] For detailed discussion of these defects and their prevention see Thomas E. Snyder, *Defects in timber caused by insects,* U. S. Dept. Agr. Dept. Bul. 1490, Washington, 1927. Contains 45 figures showing various insect defects.

[67] In American Lumber Standards a pinhole is limited to a maximum diameter of $\frac{1}{16}$ inch. *Lumber,* Simplified Practice Recommendation R16-39, U. S. Dept. Comm., Washington, 1940, p. 28.

Powder-post defects are indicated by small holes (1/16 to 1/4 inch in diameter) in the surface of the infested wood from which a characteristic granulated or flour-like powder will fall when the piece is jarred or moved. The visible openings represent the entrance and exit holes made by the adult beetles as they enter the wood to deposit their eggs and emerge from it to spread the damage; the powder is the boring dust or droppings made by the larvae or grubs as they bore through the interior of the wood for food and shelter. These larvae honeycomb the interior of the wood with their irregular burrows and may reduce its strength practically to zero, although the thin outer shell remains more or less intact.

There are a number of so-called powder-post beetles, but the most serious from the standpoint of prevalence and extent of damage are the *Lyctus* beetles, which confine their activities to the seasoned sapwood of certain hardwoods. Oak, ash, and hickory are especially susceptible to attack, although maple, walnut, persimmon, cherry, elm, poplar, and sycamore and other species are also affected. Powder-post damage to lumber, woodwork of buildings, furniture, implement handles, vehicle stock, cooperage, and other products for which the afore-mentioned species are used often constitutes a serious loss.[69]

---

[68] See *Wood handbook,* rev., U. S. Dept. Agr. Unnumbered Publ., Washington, 1940, pp. 255–8.

For detailed information concerning termite damage and its prevention see:

Dudley F. Holtman, *Wood construction—principles, practice, details,* McGraw-Hill Book Co., New York, 1929, Chap. 7.

T. E. Snyder, *Preventing damage by termites or white ants,* U. S. Dept. Agr. Farmers' Bul. 1472, Washington, 1926.

T. E. Snyder, *Tests of methods of protecting woods against termites or white ants,* U. S. Dept. Agr. Dept. Bul. 1231, Washington, 1924.

T. E. Snyder, *Injury to buildings by termites.* U. S. Dept. Agr. Leaflet 101, Washington, 1933.

C. A. Kofoid *et al, Termites and termite control: a report to the termite investigations committee,* Berkeley, Calif., 1934.

Termite damage protection, *Lumber and its utilization,* Construction Information Ser. Vol. 4, Chap. 9, Nat. Lbr. Mfrs. Assn., Washington, 1928.

MINOR INSECT INJURIES

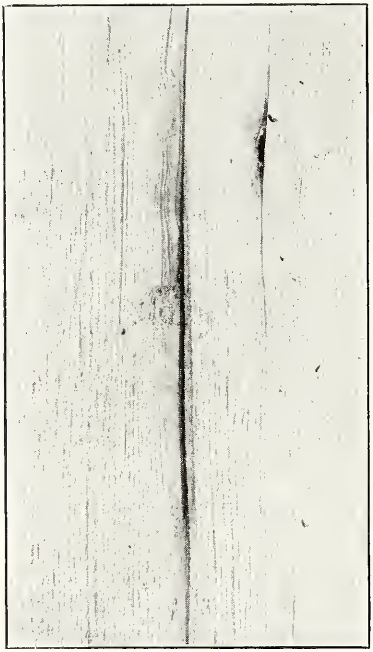
In addition to the afore-mentioned insect holes, several other forms of damage in wood are attributed wholly or in part to insect activity. Among these may be listed distortions or abnormalities of the growth rings, pitch pockets, gum spots, black streaks, and pith flecks.[70] **Ring distortions,** in the nature of double-growth rings (*false* or *secondary rings*) or incomplete annual layers of growth, are frequently formed in wood as a result of disturbances in the normal rate of growth of the tree, such as accompany marked reductions in the amount of available food. The defoliation of trees by leaf-eating insects frequently results in such a condition, but other factors, as the action of frost, drought, and hail, are also responsible. This defect has no practical effect on the strength of wood except possibly as the abrupt changes in the width of the growth rings may induce the development of shakes. **Pitch pockets** are limited openings between the annual growth rings containing more or less pitch. Their cause has not been definitely established, although insects working in living trees are held to be responsible in part. Because of their possible effect on the strength of wood, pitch pockets have been discussed more in detail in a previous section. **Gum spots** are accumulations of gum-like substances occurring as small patches or streaks in wood. They are formed in living western hemlock and Douglas fir trees, as a result of attack by the grubs of various insects but in these and in other woods may also occur in conjunction with bird pecks or other forms of injury to the growing wood.

Black streak (Fig. 34) is a defect produced in western softwoods by the larvae of small flies (*Cheilosia* spp.) or moths (*Parharmonia* spp.), and in oak by the larvae of large beetles that work in the cambium of living trees and form small pockets in the outer layers of the wood. These cavities are subsequently healed over, but the wood about them is stained dark, and the newly formed layers are characterized by a dip in the grain at the point of injury. The original openings remain but in the conifers become filled with pitch and bear some resemblance to pitch pockets, although the grain of the wood is not so characteristically distorted in the latter defects. Black streak is especially prevalent in western hemlock but also occurs in other western conifers (fir, spruce, and ponderosa pine) and in oaks. In the conifers the checks are ½ to 1 inch long and of a like width (on tangential surface), whereas in oak they may be much larger. The effect of this type of defect is to lower the grade of finishing lumber or to make the material unfit for finishing, turning, staves, and woodenware. Except for the maggot chamber itself, which may be considered equivalent to a pitch pocket of the same size, the effect of black streak on strength may be disregarded.

---

[69] For methods of preventing powder-post damage see T. E. Snyder, *Preventing damage by Lyctus powder-post beetles,* U. S. Dept. Agr. Farmers' Bul. No. 1477, rev., Washington, 1938.

[70] Snyder, footnote 66, pp. 36–43.



Forest Products Laboratory Photo

FIG. 34. Black streak in western hemlock.

Pith flecks are narrow, usually brownish streaks, up to several inches in length on the surface of a piece, resulting from the burrowing of the maggots of flies or adult weevils in the growing tissue (cambium) of a tree. These defects normally appear on the cross section of a piece as small, half-moon-shaped patches. The most common type of pith fleck is that formed in maple (especially the soft maples), birch (chiefly in gray, paper, and river birch), poplar, cottonwood, basswood, oak, cherry, and other hardwoods by the larvae of certain flies. The adult flies lay their eggs in the young branches, and the larvae which hatch from them burrow down the trunk through the cambium to the roots, where they emerge and pupate. These tunnels become filled with outgrowths from adjacent parenchyma cells, and subsequent growth closes over them.[71] Snyder[66] also describes another pith-fleck injury that is caused by the feeding of adult weevils on the cambium of certain conifers. In this type the damage is more localized, the insects forming small cavities (¼ to 1 inch in width) in the cambium which later become filled up with parenchymatous tissue and gum. Pith flecks do not noticeably affect the strength of wood unless they are exceedingly numerous.

Bird Peck[72]

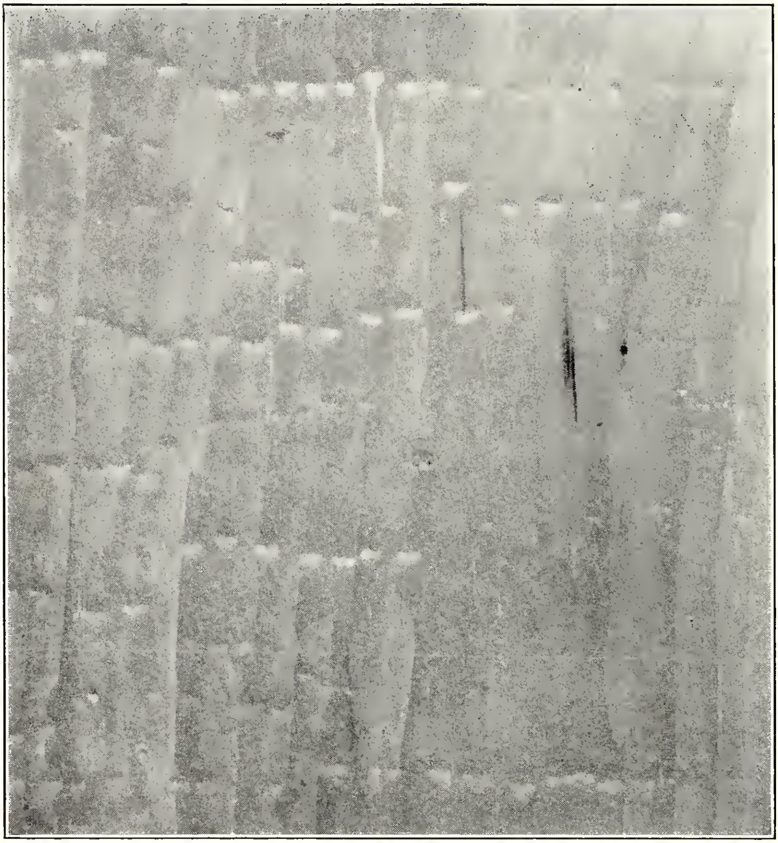
The wood of hickory, maple, yellow poplar, white ash, and many other species, including the conifers, is sometimes damaged by a group of woodpeckers, known as sapsuckers. These birds drill into the living tree through the inner bark and cambium, which they utilize for food, and often extend their workings into the outer layer of sapwood, from which they extract sap. The holes thus formed, which may be disposed in partial or complete rings around the trunk or in vertically inclined rows, are healed over, but the subsequent growth of wood is more or less distorted and occasionally gives rise to curly grain and certain forms of "bird's-eye." This type of injury is known as **bird peck** (Fig. 35) and is usually further characterized by a brown or black discoloration of the wood, extending from a few inches to as much as several feet above and below the wound. Such stains are termed **mineral streaks** (Fig. 36) and are most common in the hardwoods. They are caused by oxidation and other chemical changes in the substances in the wood.

Bird pecks are classified as defects primarily because of their effect on the appearance of wood and, in material to be used for handles, because of the tendency of the grain to roughen and splinter at the point of injury when machined. They are not usually considered to impair the strength of wood, except possibly in small pieces or when they are numerous and more or less concentrated within a given growth ring, as is sometimes the case. The concentration of these defects within the annual layers of

---

[71] H. P. Brown, *Pith-ray flecks in wood,* U. S. Dept. Agr. For. Serv. Circ. 215, Washington, 1913.

[72] For further discussion of defects produced in wood by birds see W. L. McAtee, *Woodpeckers in relation to trees and wood products,* U. S. Dept. Agr. Biol. Surv. Bul. 39, Washington, 1911.



Forest Products Laboratory Photo

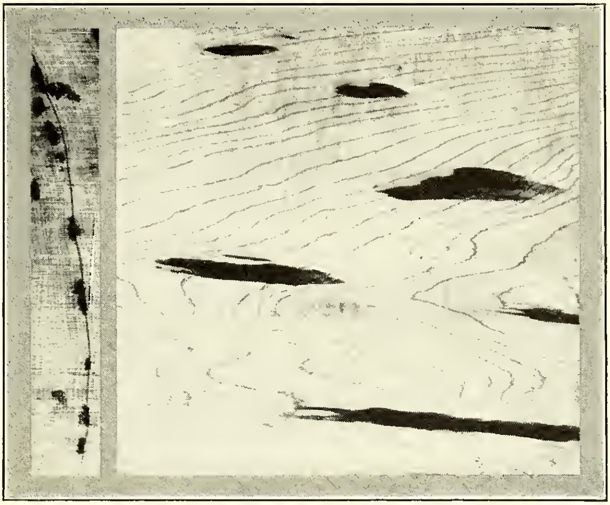
Fig. 35. Bird peck in yellow poplar veneer.

growth may lead to the development of cup shake in the standing tree.

Marine Borer Injury

Serious damage is done to the submerged portions of wood piling and other timbers used in marine construction by certain low forms of animal life, known as **marine borers.** These borers are widely distributed throughout the salt waters of the world, although more prevalent in warm regions than in cold, and are reported in the United States in practically all harbors along the

Atlantic, Gulf, and Pacific coasts. At times they become epidemic in character, and serious and often sensational destruction of marine structures results. Such an outbreak occurred in the northern part of San Francisco Bay, where from 1917 to 1921 the borers were responsible for damage estimated at $15,000,000. This epidemic destruction was occasioned primarily by a low rainfall in the region during 1917 and 1919, which decreased the discharge of fresh water from the rivers entering into the northern part of the Bay; thus the salinity of the normally borer-free water was increased to a point that made infestation possible. The epidemic continued practically as long as the available supply of unprotected wooden structures lasted. Current developments in the sanitation of New York harbor present the danger of a new epidemic as contamination by sewage has for years been relied on inadvertently for the protection of untreated piling in that harbor.



Forest Products Laboratory Photo

Fig. 36. Mineral streaks on the face and cross section of a hard maple board.

There are two distinct groups of marine wood-boring animals, each characteristic in its general structure and method of attacking wood. The most destructive individuals are the molluscan borers, popularly known as *shipworms,* which are distantly related to the oysters and clams; they belong to two genera, *Bankia* (formerly divided into *Xylotria* and *Nausitoria*) and *Teredo*. The second group comprises the crustacean borers, or *wood lice*, which are kin to the lobsters and crabs; they are confined to the genera *Limnoria*, *Sphaeroma*, and *Chelura*.

The shipworms enter wood only as larvae. The young microscopic individuals make minute entrance holes in the exposed surface of the wood, but once within the timber the animals increase rapidly in size and develop long, worm-like bodies.

The extent and rapidity of damage by shipworms depends primarily on the genus of borer involved; conditions such as temperature and salinity; and the intensity of the infestation. Under conditions extremely favorable for their development, some of the molluscan borers and their galleries may attain a total length of 4 to 6 feet and a diameter of an inch, but during heavy infestations, when there is keen competition for food and shelter, they are seldom more than a few inches long and ⅛ to ¼ inch in width. These borers usually enter the timber at right angles to the grain and then turn in the longitudinal direction and follow a very irregular, tangled course. When the infestation is heavy, some of the galleries, of necessity, extend rather deeply toward the center of the pile before turning with the grain, and the wood is reduced to a honeycombed mass within a thin protective shell and loses all structural strength at the point of attack. In extreme cases untreated piling may be rendered useless in a few months, although under less severe attack it may last for several years.

During all the time that the shipworms are growing to maturity within the wood the entrance holes are only slightly enlarged. Consequently, piling may be virtually riddled and still appear relatively sound to casual inspection. The destruction is further hidden from normal observation since the attack of the shipworms is often concentrated at or near the mud line.

Of the crustacean borers, *Limnoria* is by far the most destructive, being active along the entire Atlantic, Gulf, and Pacific coasts of the United States. It burrows into the wood to obtain both food and shelter, and attains a length of ⅛ to ¼ inch when mature. *Chelura* commonly works in conjunction with *Limnoria* and is of approximately the same size. *Sphaeroma*, on the other hand, is a more solitary worker and makes somewhat larger although fewer holes; although capable of doing serious damage, it is seldom very destructive to wooden marine structures.

The destruction of wood by the wood lice differs considerably from that by the shipworms. The galleries of these wood-boring crustaceans are of relatively small diameter (about $\frac{1}{20}$ inch in the case of *Limnoria*) and of uniform width throughout their depth and seldom extend more than half an inch below the surface of the timber, although they may run obliquely for an inch or two. Although their workings are more or less superficial, these animals commonly attack wood in such great numbers (often 200 to 400 per square inch of surface) that the outer layers are reduced to a honeycombed mass. The thin partitions of wood separating the burrows are then broken away by the mechanical action of waves or other forces, and a fresh surface is exposed to the borers, which are free to move about. Thus the destruction becomes progressive, and the volume of wood at the place of attack is gradually reduced to the point of failure.

The attacks of marine borers of this group may extend down to the mud line but appear to be most concentrated between half tide and low tide, where the washing action of the waves and the battering of floating debris materially accelerate the breaking down of the honeycombed surface. Both hard- and softwoods are attacked, but destruction is more rapid in the softwoods; this is also the case in the softer portions of those species that exhibit decided differences in density between early and late wood. When *Limnoria* works in the same timbers as the shipworms, as is frequently the case, it may eat away the wood protecting the latter and thus expose them to the attacks of their enemies.

The damage to piling and other submerged wood by crustacean borers is less serious than that caused by the shipworms, as a rule, since it is readily apparent on inspection, especially when concentrated at or near low tide. Detruction is also less rapid than from attack by the molluscan borers. Under extremely favorable conditions, *Limnoria* requires a year to accomplish the destruction that *Teredo* can perform in a few months.

Although no woods are known to be immune to destruction by the various molluscan and crustacean borers, certain species have been found to offer more or less resistance to their attacks, presumably owing to the presence of extraneous essential oils or other toxic materials, to their extreme density, or to a high silica content. Among the most resistant kinds, which are all of foreign origin, may be mentioned jarrah, totara, turpentine wood, azobe, manbarklak, angelique, and greenheart, although the last-named wood does not have an especially good record in tropical waters. Unfortunately, however, these woods are not available for general use in the United States because of their excessive cost or limited and uncertain supply. The palms have also evidenced some immunity, as a result of their peculiar structure, but they are lacking in strength and are not generally available in suitable sizes, as well as being subject to rapid decay above the water line. The two woods extensively used for piling in the United States, namely, southern pine and Douglas fir, are soon destroyed in infested waters unless they are creosoted or some other form of artificial protection is provided.[73]

Parasitic Plant Injuries[74]

The most common of the higher parasitic plants damaging timber trees are the mistletoes. Many species of deciduous trees are attacked by the common mistletoe (*Phoradendron flavescens*). This particular parasite is very prevalent in the South and Southwest and when present in sufficient quantity does considerable damage. There are also numerous smaller mistletoes belonging to the genus *Razoumofskya* which are widely distributed throughout the country, and several of these cause serious losses in coniferous timber west of the Rockies, particularly in western larch, Douglas fir, and ponderosa and lodgepole pine.

Although mistletoe is most injurious from the standpoint of its effect in impairing the vitality and growth of the trees serving as its host, it may also seriously reduce the quality of the lumber that can be produced from the infected trees. The irritation of the cambium by this parasite causes an excessive formation of parenchymatous tissue, and the wood produced near the points of attack is consequently weak. Further, in resinous conifers, resin production is stimulated, and large areas of pitchy wood result. Mistletoe attack also leads to accelerated diameter growth in the infested limbs, as well as to the formation of numerous secondary branches, thus increasing the size and number of knots in lumber sawed from the host trees. Infections on the trunks of trees commonly result in the development of burls and other irregularities, thus greatly reducing the merchantable contents of the boles and often rendering them unfit for sawing.

---

[73] For information on methods of protecting wood against marine borers see William G. Atwood and A. A. Johnson, *Marine structures—their deterioration and preservation,* Nat. Res. Coun., Washington, 1924.

Also C. L. Hill and C. A. Kofoid, *Marine borers and their relation to marine construction on the Pacific Coast,* Univ. Calif. Press, Berkeley, 1927.

[74] Harlan H. York, *The anatomy and some of the biological aspects of the "American mistletoe,"* Univ. Texas Bul. 120, Sci. Ser. 13, Austin, 1909.

Wm. L. Bray, *The mistletoe pest in the Southwest.* U. S. Dept. Agr. Bur. Plant Ind. Bul. 166, Washington, 1910.

James R. Weir, *Mistletoe injury to conifers in the Northwest,* U. S. Dept. Agr. Bul. 360, Washington, 1916.

Clarence F. Korstian and W. H. Long, *The western yellow pine mistletoe,* U. S. Dept. Agr. Bul. 1112, Washington, 1922.

Frost Injuries

Standing timber in cold climates frequently develops defects known as **frost splits, or frost cracks.** These injuries consist of radial separations which extend inward from the periphery of a tree, usually, if not always, near the base. They are most common in trees that split readily and in those with large rays and thin bark. The primary cause of the splitting is thought to be frost, and various theories have been advanced to explain the action.[75]

Such cracks not only affect the strength and value of wood directly, but also provide a point of entrance into the living tree for decay. Since they occur only at or near the base of the tree, these separations are confined to the ends of lumber or timbers produced from the butt log; they extend at right angles to the growth rings and are accordingly classed and graded as checks. Like checks, they may materially reduce the area resisting shear and, consequently, in members subjected to bending, are most serious when they extend along the neutral plane.

A less conspicuous type of frost injury is the **frost ring,** which appears as a brownish line or zone extending partly or entirely around the stem within a given annual-growth layer. Such defects are produced in the wood of living trees as the result of action of early or late frosts during the growing season or of the cambium while the tree is dormant.[76] It is evident that frost rings, because of their abnormal structure and the predominance of storage tissue, afford a plane of weakness in the wood, not only making the affected tree liable to the development of ring shake but also decreasing the strength of the manufactured product which contains them, especially when the material is used in small sizes.

---

[75] R. Hartig, *Text-book of the diseases of trees,* trans. by Somerville and Ward, Macmillan & Co., London and New York, 1894, pp. 282–94.

Also W. Busse, Frost-, Ring- und Kernrisse, *Forstwiss. Centralb.,* Vol. 32, Feb. 1910, pp. 74–81.

Lightning Rings[77]

The common form of lightning injury is readily discernible in standing trees because of the conspicuous stripping of the bark on the trunks and main branches. Spike tops and stag heads also result from the often extensive damage to the cambium and inner bark and the further loss in vitality occurring with subsequent decay and insect attack. Another form of injury, which is not apparent until the tree is felled and worked up into lumber, is the so-called **lightning ring.** Such a ring is produced as the result of the irritation of the cambium by an electric discharge and is characterized by the formation of a layer of abnormal cells. In certain of the conifers such layers contain numerous traumatic resin ducts, whereas in others enlarged resin cells are laid down. Since it is produced by cambial activity, each lightning ring is confined entirely within a given annual layer of growth, although it may extend partly or entirely around the stem, as well as varying distances up and down the tree trunk. For this reason these defects may have somewhat the appearance of false- or secondary-growth rings, an effect frequently accentuated by the discoloration that also accompanies them.

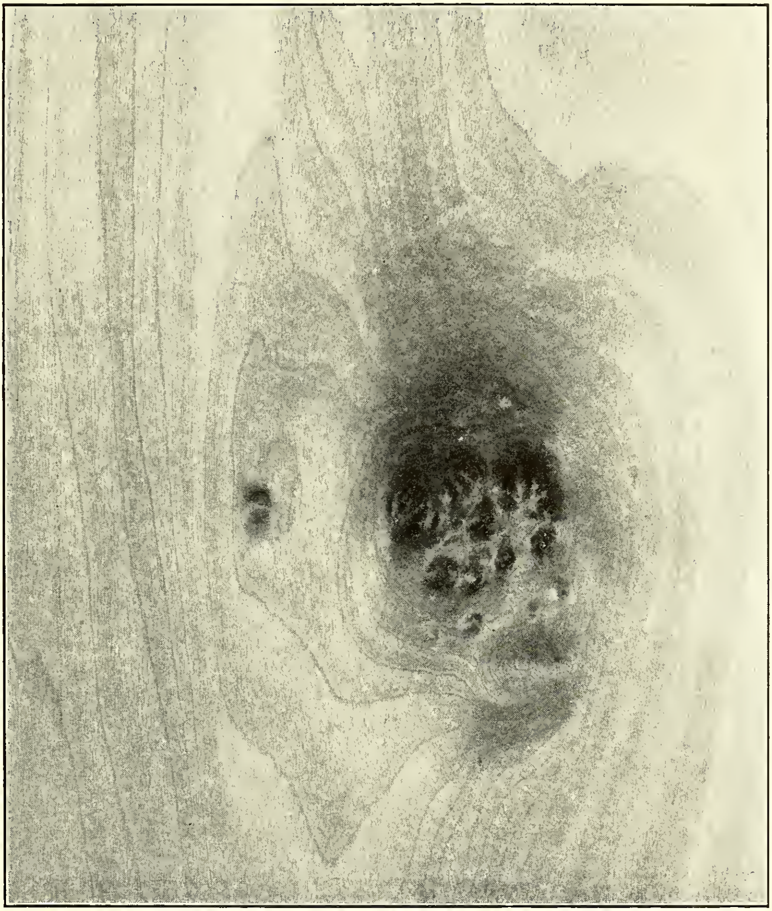
Lightning rings, because of the character of the tissues comprising them, form natural planes of weakness in wood and may, therefore, seriously weaken it in resistance to shear. Such formations are also subject to a form of checking which is quite distinctive, since the separations extend tangentially with the growth rings rather than at right angles to them.

---

[76] Arthur S. Rhoads, *The formation and pathological anatomy of frost rings in conifers injured by late frosts,* U. S. Dept. Agr. Dept. Bul. 1131, Washington, 1923.

Also M. Y. Orr, The effect of frost on the wood of larch, *Trans. Royal Scottish Arbor. Soc.,* Edinburgh, Vol. 39, Pt. 1, 1925, pp. 38–41.

[77] J. S. Boyce, *Decays and discolorations in airplane woods,* U. S. Dept. Agr. Bul. 1128, Washington, 1923, pp. 17–19.



Forest Products Laboratory Photo

Fig. 37. A burl formed by a cluster of dormant buds in yellow poplar veneer.

Burls

The term burl has several distinct meanings.[78] A burl may be a large excrescence occurring on the bole of a tree and containing a large number of buds that usually fail to develop. Highly figured burl veneers are cut from this type of growth. The term also applies to a swirl in the grain of wood in the vicinity of a knot. This definition has been used for many years in the grading of hardwood lumber. For aircraft inspection purposes, a burl in rotary-cut veneer has been defined as localized severe distortion of the grain due to one or a cluster of small conical protuberances, each with a core, or pith, but without an appreciable amount of end grain surrounding it (Fig. 37).

---

[78] *Wood aircraft inspection and fabrication,* footnote 49, pp. 91–4.

Because of the character of the cross grain associated with it, the weakening effect of a burl is usually less than that of a knot of the same size.

Floccosoids[79]

Floccosoids are harmless, whitish deposits occasionally found in the cell cavities of western hemlock that, because of their appearance as white spots or streaks (Fig. 38), are sometimes mistaken for pocket rot (*Fomes pini*). Under the microscope they exhibit a thread-like crystalline structure in the cell cavities. Floccosoids are soluble in potassium hydroxide solution and are thus readily distinguished from decay. Wood containing floccosoids retains its normal properties.

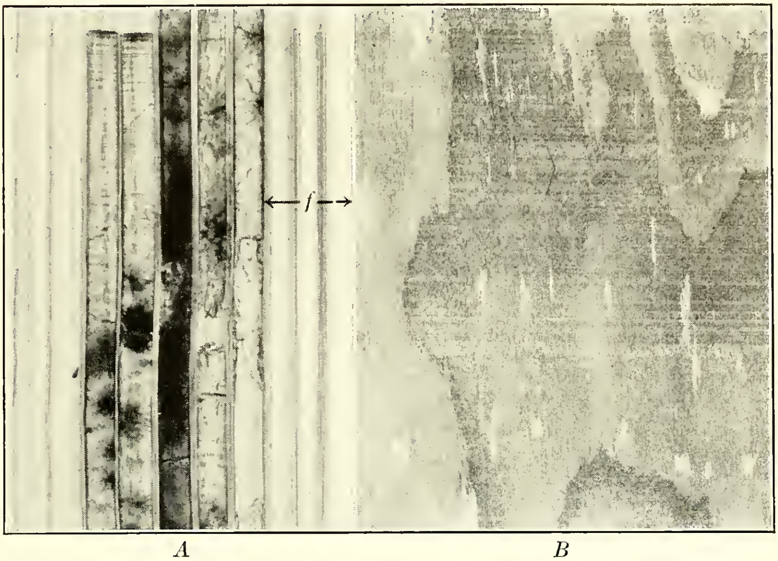
Indented Rings

Indented rings (Fig. 39) are irregularities traceable to abnormal cambial activity and are not uncommon in certain coniferous woods including Douglas fir and Sitka spruce. As seen on the cross section, consecutive growth rings are typically indented along the same radii, often for many years. On a tangential section each indentation is shown to extend several inches longitudinally in an irregular wavy course (Fig. 39*B*) that has led to the application of the name "bear scratches" to these blemishes.

[79] Eloise Gerry, *Western hemlock "floccosoids" (white spots or streaks)*, For. Prod. Lab. Rept. 1392, Madison, 1943.

Also Bror L. Grondal and Arthur L. Mottet, Characteristics and significance of white floccose aggregates in the wood of western hemlock, Univ. of Washington *For. Club Quart.*, Seattle, Vol. 16, No. 1, 1942, pp. 13–18.

Also *Wood aircraft inspection and fabrication,* footnote 49, pp. 99, 101.



Forest Products Laboratory Photo

FIG. 38. Floccosoids in western hemlock. *A*. Photomicrograph showing floccosoids in the cell cavities (about 150 times). *B*. Floccosoids in rotary-cut veneer.

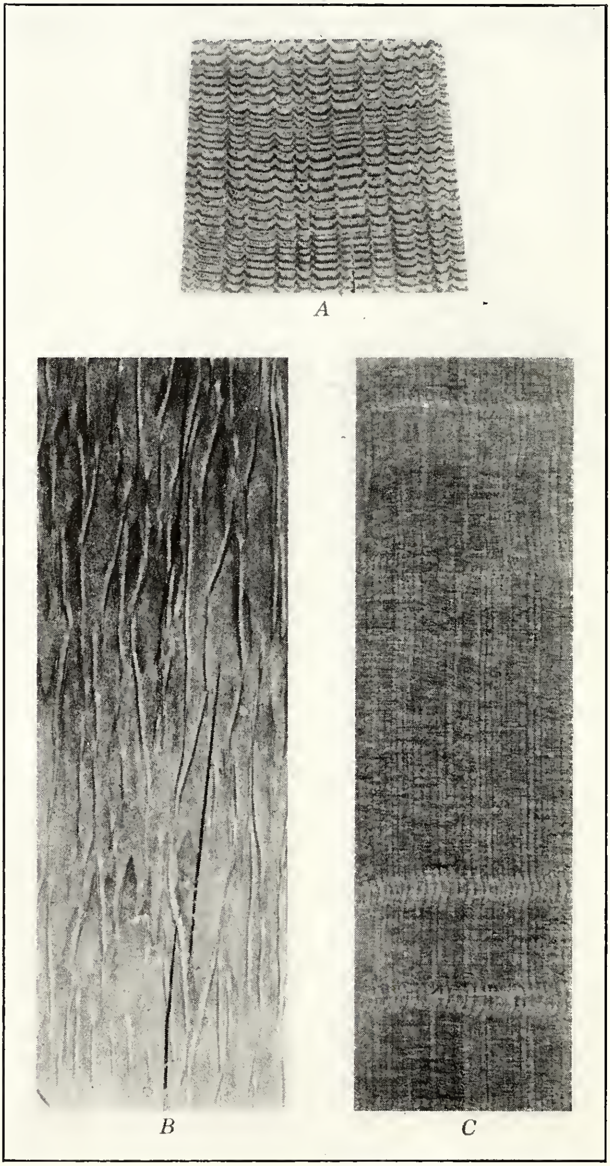
That grain direction in the tangential plane is not affected by indented rings is shown by the direction of the checks in the figure. The only distortion of grain associated with indented rings is a very slight radial dip (Fig. 39*C*) insufficient to affect the properties of the wood.

Red Radial Streak in Spruce

Red radial streaks occur occasionally in spruce and appear as dark reddish streaks extending across the growth rings as seen on the radial surface (Fig. 40). Their color is caused by a dark, gummy material contained in the ray cells. Although sometimes associated with distorted grain, the red streaks, in themselves, are not a source of weakness.

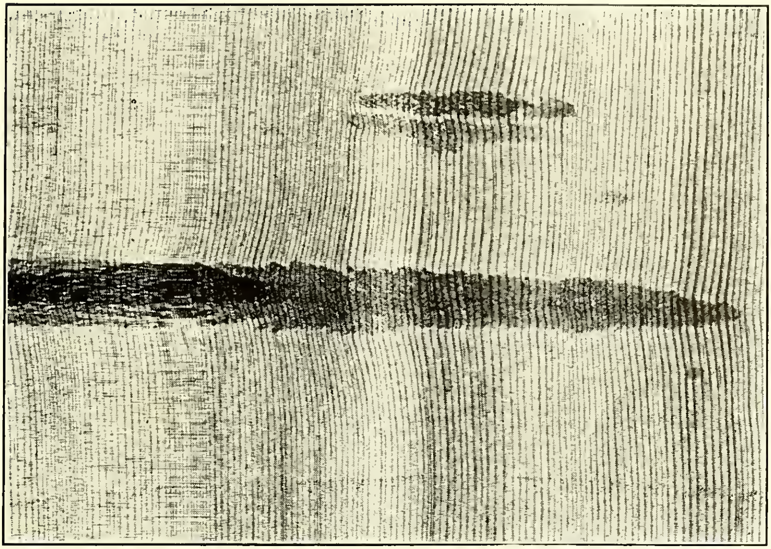
Pith

Pith is the small, soft, nonwoody core in the tree, about which the annual rings of growth are laid. It normally is near the



Forest Products Laboratory Photo

Fig. 39. Indented rings in Sitka spruce. *A*. Cross section. *B*. Tangential surface (note that checks indicative of grain direction are not affected by indentations.) *C*. Radial surface.



Forest Products Laboratory Photo

FIG. 40. Red radial streak in Sitka spruce.

geometric center of the trunk of the tree, but, when growth is eccentric, as in leaning trees or those whose branches are developed more on one side than the other, it may be decidedly "off center" (see Fig. 30*A*). Because of its location in the tree and log, the pith is frequently included in large structural timbers, and such pieces are designated as *boxed-heart* timbers. Timbers that do not contain the pith are sometimes termed *side-cut* pieces. The wood immediately surrounding the pith is often characterized by abnormal cell-wall structure of low quality and contains small checks, shakes, or numerous pin knots; any such combination of defects and blemishes is known as *heart center*. Because of its small size the pith itself does not have any apparent effect on the strength of boxed-heart timber, but the associated checks and shakes may seriously reduce the area resisting shear and should, therefore, be limited to the same extent as any other checks or shakes.

Wane

Lumber and other forms of wood are sometimes characterized by the presence of bark, or by a lack of wood, on the otherwise square edges or corners of a piece. This condition, which is termed **wane,** is commonly considered a defect, although it is usually limited in grading rules by such factors as bearing area, nailing edge, and appearance, rather than by its direct effect on strength.

FACTORS OTHER THAN DEFECTS

In selecting wood for exacting strength requirements it is not necessarily sufficient that a strict limitation be placed on the visible defects. A wide variation is recognized in the strength of the clear wood itself, a factor usually associated with differences in the density of the material and with the variable conditions under which it was grown. The moisture content of the wood may also have a bearing on its strength, especially in the smaller sizes, whereas the treatment the material receives in preparing it for use may be of considerable importance, particularly when it involves exposure to high temperatures. For some uses heartwood is discriminated against; for others sapwood is considered objectionable. And finally, prejudice is not infrequently voiced against material cut from dead trees, as well as that from living trees felled at certain seasons of the year. It is the purpose of the ensuing paragraphs to discuss the relation of these several factors to the strength of wood.

Density

It has long been recognized that, aside from actual strength tests, the **density,** or **specific gravity,**[80] of a specimen of wood is the most satisfactory criterion of its clear-wood strength. In fact, within a given species for which the average density and strength values are already known, it may be even more satisfactory than the actual testing, since specific-gravity determinations are relatively easy to make and require no adjustment such as would be necessary on account of the varied conditions of a strength test.

---

[80] Density is merely the weight of a unit of volume of a given material, as 35 pounds per cubic foot, or 0.56 gram per cubic centimeter. Specific gravity, or relative density, is the ratio of the density of any material to the density of distilled water at 4°C. (39.2°F.). A cubic foot of distilled water at 4°C. weighs 62.4 pounds. Since wood normally contains a variable quantity of moisture, the specific gravity of wood is commonly based on the weight of moisture-free wood and the volume at the moisture content under consideration. Hence, a piece of green wood weighing 50 pounds per cubic foot and containing 60 percent moisture (based on its oven-dry weight) has an oven-dry weight of 31.2 pounds per cubic foot of green volume ($50 \div 1.60 = 31.2$), and its specific gravity would be $31.2 \div 62.4 = 0.50$ (based on oven-dry weight and green volume). In the metric system, since the weight of a cubic centimeter of pure water is one gram, the oven-dry weight in grams per cubic centimeter has the same numerical value as the specific gravity. For details as to procedure in determining specific gravity, see page 365.

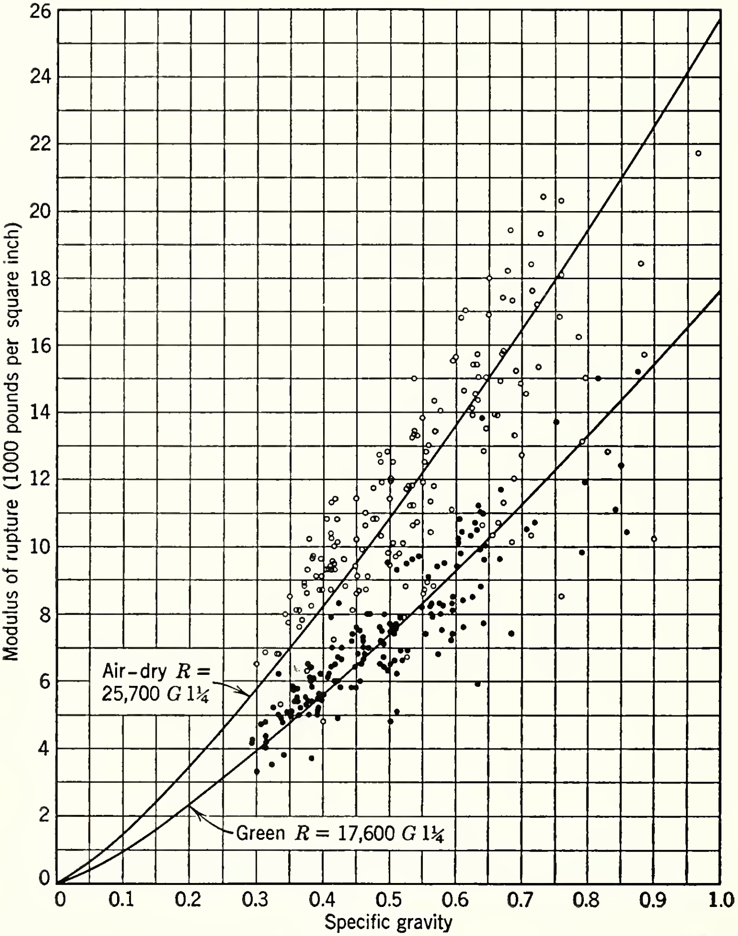
The density of the actual wood substance, that is, the material that constitutes the walls of the fibers and other cells and gives to wood its strength, may, for practical purposes, be considered the same in all species, whether pine, oak, or cottonwood. Its specific gravity has been determined to be approximately 1.5[81] Leaving out of consideration the possible presence of extraneous materials, such as gums, resins, and the like, the reason then that one wood exceeds another of the same approximate degree of dryness in density, or weight per cubic foot, is simply that it contains a greater amount of wood substance. The variability in density of our American woods is indicated in Table 1, which shows a range in specific gravity (based on oven-dry weight and unseasoned volume) of from 0.28 for corkbark fir to 1.04 for black ironwood. The greater amount of wood substance in one wood than in another is reflected in the presence of a larger proportion of cells with thicker walls and smaller cavities, a condition that naturally leads to greater strength on the part of the denser wood.

Approximate relations between the specific gravity and various strength properties of wood have been worked out by the Forest Products Laboratory and expressed in the form of a series of equations (see Table 9). The relationship between modulus of rupture and specific gravity for a large number of species is shown graphically in Fig. 41. Some properties, such as endwise compressive strength (maximum crushing strength and fiber stress at proportional limit in compression parallel to grain) and stiffness (modulus of elasticity in compression and in static and impact bending), have been found to vary directly with specific gravity, whereas the others change at an exponential rate. For example, bending strength (fiber stress at proportional limit and modulus of rupture in static bending) changes slightly more than

---

[81] A study of seven American species, including both conifers and hardwoods, showed an extreme range of only about 4½ percent from this value. See Frederick Dunlap, Density of wood substance and porosity of wood, *Jour. Agr. Res.*, Washington, Vol. 2, Sept. 21, 1914, pp. 423–8.

Also A. J. Stamm, Density of wood substance, absorption by wood, and permeability of wood, *Jour. Phys. Chem.* Vol. 33, 1929, pp. 398–414.



Forest Products Laboratory

FIG. 41. Relationship between modulus of rupture and specific gravity for green and air-dry wood.

the corresponding specific gravity, whereas toughness or shock-resisting ability (work to maximum load in static bending and height of drop causing complete failure in impact bending) varies almost as the square of specific gravity. Thus, one piece of wood that has twice the density of a second would be expected to have double the stiffness and endwise crushing strength, about 2½ times the bending strength, and approximately 3½ times the toughness of the second.

Although the afore-mentioned relations apply generally to wood of different species, variations due to the characteristics of individual species are sometimes of considerable magnitude. For example, Douglas fir (coast type) and red gum are about equal in density; yet the fir averages 39 percent higher in endwise compressive strength than the gum and 18 percent lower in shock resistance. Furthermore, Douglas fir (coast type) is about equal to commercial white oak in bending and endwise compressive strength, and exceeds it in stiffness, although its density is only about three-fourths that of the oak. White oak averages much higher than the fir in hardness and shock resistance, however.[82] Such differences are to be expected because of the wide variations in wood structure among species and the relatively large amounts of resin and other extractives, characteristic of certain species, that do not contribute appreciably to the strength of the wood.

The relations expressed in Table 9 have been obtained from averages for a great many different species. Within any single species the rate of change in strength with changes in density is usually somewhat greater than that indicated. Factors for use in calculating variation in strength properties due to differences in specific gravity within a species are given in Table 10. Strength at any particular specific gravity may be computed if the proper value for n is substituted in the equation:[83]

$$\frac{S}{S'} = \left(\frac{g}{g'}\right)^n \tag{9}$$

in which S = strength corresponding to specific gravity, g; and S' = strength corresponding to specific gravity, g'.

To estimate the modulus of rupture of a specimen of red ash at 12 percent moisture content with a specific gravity of 0.75, aver-

---

[82] L. J. Markwardt, *Comparative strength properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 158, Washington, 1930, p. 15.

[83] Forest Products Laboratory, *Design of wood aircraft structures,* ANC Bul. 18, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1944, p. 15.

Table 9. Relations of Strength Properties to Specific Gravity Applicable to Wood of Various Species*

Property	Unit	Equation †	
		Unseasoned Wood	Air-Dry Wood (12% Moisture Content)
Static Bending			
Fiber stress at proportional limit	Psi	$10{,}200G^{1.25}$	$16{,}700G^{1.25}$
Modulus of rupture	Psi	$17{,}600G^{1.25}$	$25{,}700G^{1.25}$
Modulus of elasticity	Psi	$2{,}360{,}000G$	$2{,}800{,}000G$
Work to maximum load	In.-lb./in.^{3}	$35.6G^{1.75}$	$32.4G^{1.75}$
Total work	In.-lb./in.^{3}	$103G^2$	$72.7G^2$
Impact Bending			
Fiber stress at proportional limit	Psi	$23{,}700G^{1.25}$	$31{,}200G^{1.25}$
Modulus of elasticity	Psi	$2{,}940{,}000G$	$3{,}380{,}000G$
Height of drop causing complete failure	In.	$114.0G^{1.75}$	$94.6G^{1.75}$
Compression Parallel to Grain			
Fiber stress at proportional limit	Psi	$5250G$	$8750G$
Maximum crushing strength	Psi	$6730G$	$12{,}200G$
Modulus of elasticity	Psi	$2{,}910{,}000G$	$3{,}380{,}000G$
Compression Perpendicular to Grain			
Fiber stress at proportional limit	Psi	$3000G^{2.25}$	$4630G^{2.25}$
Hardness			
End surface	Lb.	$3740G^{2.25}$	$4800G^{2.25}$
Radial surface	Lb.	$3380G^{2.25}$	$3720G^{2.25}$
Tangential surface	Lb.	$3460G^{2.25}$	$3820G^{2.25}$

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935.

† The values listed in this table are to be read as equations, for example: Modulus of rupture for unseasoned material $= 17{,}600G^{1.25}$, where G represents the specific gravity, based on oven-dry weight and volume at moisture condition indicated.

age values for strength and specific gravity (Table 2) are substituted in the equation for S' and g', respectively.

$$\frac{S}{14{,}300} = \left(\frac{0.75}{0.66}\right)^{1.50} = 17{,}300 \text{ pounds per square inch}$$

Since specific gravity is such a valuable index to the strength properties of wood, it is customary to include values for it in tables of strength data (see Tables 1 and 2). Such values are usually computed from oven-dry weight and volume at the time of test (unseasoned or air-dry condition) or in the oven-dry condition.[84] Because of the shrinkage that takes place when wood dries, a block of wood measuring a cubic foot when wet, or even air-dry, will measure appreciably less when oven-dry. Accordingly, the ratio of the *weight* of the specimen when *oven-dry* to the weight of volume of water equal to the *volume* of

TABLE 10. EFFECT OF VARIATION IN SPECIFIC GRAVITY ON STRENGTH PROPERTIES WITHIN A PARTICULAR SPECIES*

Static Bending	n†
Fiber stress at proportional limit	1.50
Modulus of rupture	1.50
Modulus of elasticity	1.25
Work to maximum load	2.00
Total work	2.25
Impact Bending	
Fiber stress at proportional limit	1.50
Modulus of elasticity	1.25
Height of drop	2.00
Compression Parallel to Grain	
Fiber stress at proportional limit	1.25
Maximum crushing strength	1.25
Modulus of elasticity	1.25
Compression Perpendicular to Grain	
Fiber stress at proportional limit	2.50
Hardness	
End, radial, tangential	2.50

* From Forest Products Laboratory, *Design of wood aircraft structures,* ANC Bul. 18, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1944, Table 2–1.

† Value n is the exponent used in the equation $\frac{S}{S'} = \left(\frac{g}{g'}\right)^n$ (see equation 9).

---

[84] The volume of the wood when wet is usually the most convenient basis for computation, since it represents an extreme condition which can be easily duplicated and since the unseasoned wood will not take on moisture and swell when immersed in water in making the volume determination; likewise, the oven-dry weight has an advantage, since it also represents an extreme and constant condition which can be readily duplicated.

the specimen *at time of test* does not represent the true specific gravity of a piece of oven-dry wood. Nevertheless, because of ease of application of this method to the specimens subjected to mechanical tests, it has been generally adopted as standard practice.

It is evident that, since the volume of wood varies with the moisture content,[85] the specific gravity values derived from a given specimen will differ according to the bases on which these two factors are computed. Consequently, it is essential that the circumstances under which they were determined be clearly stated in connection with data on specific gravity.

ESTIMATION OF DENSITY

It is evident that considerable importance should be attached to practical methods of estimating the density of wood that is intended to meet exacting strength requirements. Three such methods are applicable, with certain reservations, to the visual inspection of lumber, structural timbers, and other forms of wood, based on the selection of material for (1) relative weight, (2) percent of summerwood, and (3) rate of growth.

Relative Weight. Since the amount of actual wood substance in a given piece of wood has a direct bearing on its density, or weight per cubic foot, it would appear that the selection of material on the basis of relatively great weight would offer a ready means of securing wood high in strength properties. Difficulties arise, however, since differences in weight may not be entirely due to differences in amount of wood substance. Certain woods are characterized by the presence of varying amounts of extraneous materials, such as resins and gums, that may alter the weight of the wood appreciably without correspondingly affecting its strength.[86] The resin content of pine usually constitutes 2 to 9 percent of the dry weight of the wood and that of Douglas fir about 1 percent, but occasional pieces of these woods are found in which resin comprises as much as one third of the weight. An abundance of sound knots may also affect the weight to some degree, since the wood comprising such defects is denser than the normal wood. However, material containing sufficient knots to increase its weight appreciably would normally be rejected because of the reduction in strength brought about by these defects.

---

[85] For further discussion of relation of specific gravity to changes in moisture content see Samuel J. Record and Harry D. Tiemann, Some fundamental considerations of specific gravity, *Tropical Woods,* New Haven, No. 6, June 1, 1926, pp. 5–11.

Also J. D. MacLean, Moisture content, specific gravity, and air space in wood, *Trans. Am. Soc. Mech. Eng.,* New York, Oct. 1933, WDI-55-7, pp. 55–61.

[86] See discussion of resin or pitch, page 125.

The most variable factor affecting the weight of wood is the moisture content, which may range from as low as 4 or 5 percent in kiln-dried material to more than 125 percent in the unseasoned sapwood of some species. The weight per cubic foot of various American woods in the unseasoned condition and at 12 percent moisture content is indicated in Table 6. Even in air-dried stock there may be a marked difference in the moisture content of two boards, owing to variations in drying period, exposure, and other factors; this is particularly true of sizeable timbers, which may show a marked difference in moisture content between the interior and exterior portions. Below the fiber-saturation point of wood a decrease in moisture content (and consequently in weight) is accompanied by an increase in clear-wood strength in most properties, thus further complicating the use of relative weight as a criterion of strength. However, in material of structural sizes the seasoning of wood normally results in the development of checks and other defects, that tend to offset the increase in strength due to the drying; accordingly, in practice, the strength of such material is not usually considered to be increased by drying.

Since the weight of wood is influenced to an appreciable extent by these several factors, it is apparent that it is a very indefinite quality, especially if the approximate moisture content of the wood is not known. For this reason it is not generally used as a means of selecting material for great strength. However, the minimum-strength values that may be expected from a given lot of lumber can be raised considerably by the rejection of noticeably lightweight material. Recognition is given to this fact in the basic provisions for the selection of structural material, adopted as American Lumber Standards, which specify that "no pieces of exceptionally light weight shall be permitted in any grade."

Percent of Summerwood. To understand the relation of summerwood to the density of wood it is first necessary to consider briefly the general structure of the material.[87] A tree increases in diameter by the formation under the bark of layers of wood which completely envelope the entire stem, living branches, and roots. Under normal conditions one such layer is laid down each year. In cross section, as on the end of a log, these layers appear as more or less concentric rings, and for this reason they are commonly known as *annual rings* or *growth rings* (see Fig. 30*A*). Such rings are composed of cells of various kinds but for the most part fibrous and extending with the grain of the wood.

If one examines the smoothly cut end (cross section) of a piece of wood, he will find, as a rule, that each growth ring is made up of two more or less well-defined parts. That originally nearest the pith, which was formed in the spring of the year and is consequently known as *springwood* or *early wood,* is generally more open textured and of lighter color than the outer portion of the ring, which was laid down in the summer and early fall and accordingly termed *summerwood* or *late wood.*

In the conifers (pines, spruces, hemlocks, cedars, and the like) the cells composing the growth rings are mostly of one kind (known as tracheids) and the material is consequently rather uniform in structure (see Fig. 2). Accordingly, the distinction between the two portions of the growth rings in this class of timber is brought about by a contrast between the larger, thinner-walled tracheids in the springwood and the smaller and denser cells in the summerwood. In some of the conifers, the white pines for example, there is only slight contrast between the two portions, and as a result the wood is very uniform in texture and easy to work. In the southern pines and Douglas fir, on the other hand, the summerwood is usually very dense and deep colored, presenting a very marked contrast to the soft, straw-colored springwood (see Figs. 46 and 47).[88]

---

[87] For more detailed discussion of the structure of wood see Samuel J. Record, *Identification of the timbers of temperate North America,* John Wiley & Sons, New York, 1934.

Also H. P. Brown, A. J. Panshin, and C. C. Forsaith, *Wood technology, Vol. I, Structure, identification, defects, and uses of the commercial woods of the United States,* McGraw-Hill Book Co., New York, 1948.

[88] For a discussion of the results of tests designed to show the relative strength of springwood and summerwood layers, see C. C. Forsaith, *The*

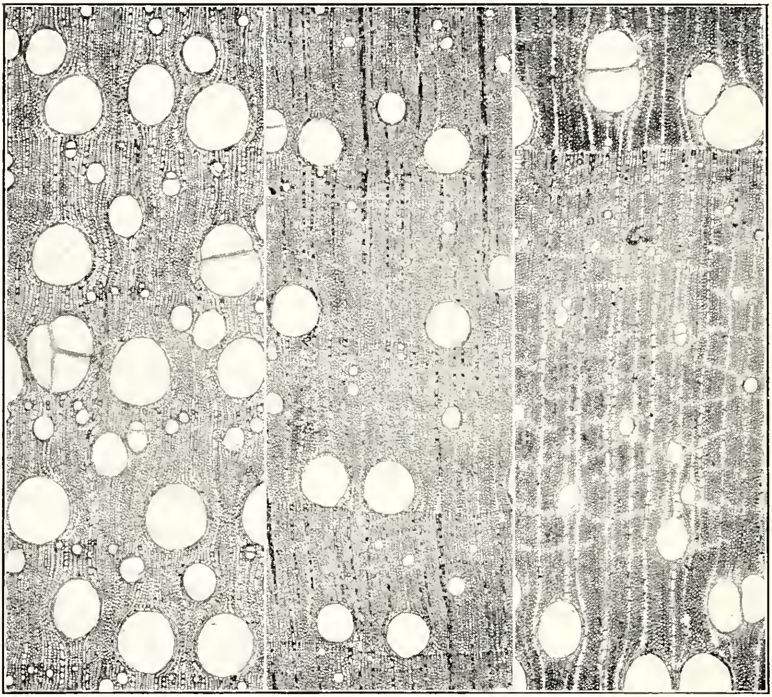
In the hardwoods the structure is more complex, the ground mass in most species being made up largely of wood fibers and vessels, or pores as they are known on cross section. The wood fibers do not exhibit any pronounced range in size, for the most part, but the vessels may show a marked variation. In certain woods (such as oak and ash) some of the vessels are large and distinct to the unaided eye; in others (poplar, gum, and the like) they are all so small as to be practically indiscernible without a hand lens. The fibers are the elements that give density and strength to a wood, while the vessels are a source of weakness.

On the basis of the arrangement of the pores (vessels) on cross section, the hardwoods are divided into two groups, namely *ring-porous* and *diffuse-porous hardwoods.* In the former group, to which belong oak, chestnut, elm, ash, and hickory, the springwood is made up, as a rule, of large pores and relatively few wood fibers, whereas the summerwood is composed of smaller pores and a much larger proportion of fibers (see Fig. 42). Because of the contrast between the porous springwood zone and the denser summerwood band, the growth rings in the ring-porous woods are always well defined. In the diffuse-porous hardwoods, such as maple, birch, beech, gum, poplar, and basswood, the pores are usually more nearly of the same size and scattered rather uniformly throughout the annual-growth layer (see Fig. 43). As a result, there is often little, if any, contrast in density between springwood and summerwood in the diffuse-porous group. Also the growth rings are frequently rather poorly defined; in some instances they may be practically indiscernible to the unaided eye.

It is apparent from the foregoing discussion that, in the ring-porous hardwoods and those species of conifers exhibiting a pronounced difference in density between the two parts of the growth ring, the ratio of dense summerwood to the more open-textured springwood affords a practical means of estimating the relative density and therefore the probable strength of different pieces of the same kind of wood. Among the conifers sufficient contrast is lacking in most of the species, and it is only in southern pine and Douglas fir that an accurate determination of summerwood can be made by visual inspection. Accordingly, the basic provisions for the selection of structural material, adopted as American

---

strength properties of small beams (match stick size) of southern yellow pine, N. Y. State Col. For. Tech. Publ. 42, Syracuse, 1933.



Forest Products Laboratory Photo

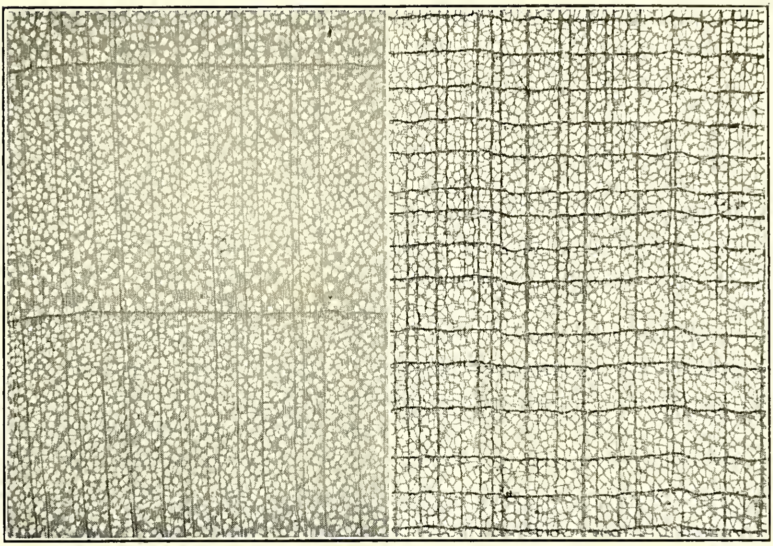
Fig. 42. Cross sections of hickory showing effect of changes in rate of diameter growth on the structure of a ring-porous wood. *Left,* wood of slow growth and low density and strength, such as is usually found near the circumference of old-growth trees; *center,* wood of moderate growth and relatively high density and strength, which may be found near the center of trees that originate in the virgin forest; *right,* wood of rapid growth and high density, such as is commonly found in "second-growth" material. ×22½.

Lumber Standards, provide a *density rule* for the selection of material of these two woods for the highest quality for strength purposes. This requires that Douglas fir and southern pine timbers shall show an average of one-third or more summerwood as measured at a specified place.[89]

In the visual inspection of wood for density, however, not only the proportion of summerwood but also its quality should be taken into consideration. In the ring-porous hardwoods, for example, specimens containing wide bands of summerwood are sometimes relatively low in density, owing to a rather porous condition of the normally dense late wood or to an abnormally high proportion of parenchymatous tissue in this portion of the growth ring. This is especially so with oak and ash,[90] and wood of these species intended for exacting strength purposes should be selected for relative weight as well as percentage of summerwood.

---

[89] For details of measurement of summerwood see pages 233–5.



Forest Products Laboratory Photo

FIG. 43. Cross sections of yellow poplar showing the effect of change in rate of diameter growth on a diffuse-porous wood. *Left,* wood of rapid growth and relatively high specific gravity (0.41), produced during the early life of the tree under favorable conditions; *right,* wood of slow growth and low specific gravity (0.31), produced after the tree had suffered a reduction of its crown due to many years of crowding. ×10.

Rate of Growth. In certain species of wood there appears to be some correlation between density and rate of growth, the latter being indicated by the number of growth rings per inch, as measured on the cross section along a representative radial line. In other words, in such woods there is a rather definite range in number of rings per inch that is frequently associated with relatively high density. There has been a tendency to overemphasize the importance of this relation in the past, however, and in no case should rate of growth be given preference over actual density in selecting material for strength. The quality of the wood must be considered as well as the width of the growth rings.

---

[90] There is a type of ash, known to the trade as "pumpkin ash," that possesses a relatively high proportion of summerwood but is low in specific gravity. Such material breaks under comparatively light loads and with a characteristic brash, or brittle, failure, when subjected to static or impact bending. This type of wood is often characteristic of the several species in the white ash group when grown under swampy conditions in the southern part of their range. It is not to be confused with the wood of *Fraxinus tomentosa,* a distinct species, which is known under the common name of pumpkin ash.

Since the anatomical characteristics of wood play an important part in determining its density and strength, it is necessary to consider the three classes of timber—conifer, ring-porous hardwood, and diffuse-porous hardwood—separately. In the conifers it is evident, from the previous discussion, that any condition affecting the relative proportion of thick-walled summerwood tracheids and thin-walled springwood cells will influence the density of the wood. This is particularly true in those species, such as southern pine and Douglas fir, that show a marked contrast in density between the two portions of the growth ring and possess definite bands of each. In general, it may be said that in the conifers both very wide and very narrow growth rings usually contain a smaller proportion of summerwood than rings of intermediate width. Consequently, the specimens representing either extreme of growth are normally lower in density than those of average growth. This fact is recognized in the basic provisions for structural material of American Lumber Standards which specify a so-called *ring-count* rule for the dense grades of Douglas fir and southern pine and for close-grained Douglas fir and redwood.[91]

In comparing specimens of a given ring-porous hardwood, showing various rates of growth, it may be noted that, as the width of the growth rings increases, the porous springwood zone does not usually increase in proportion. Accordingly, the wider growth rings usually contain a greater percentage of summerwood in which the thick-walled, strength-giving fibers abound than do the narrower ones (see Fig. 42). For example, in oak of good quality and rapid growth, the large pores or vessels of the springwood may occupy 6 to 10 percent of the volume of a timber, whereas in weaker material of slow growth they may make up 25 percent or more. For this reason, it is commonly stated that, in ring-porous hardwoods, the more rapid the growth or the wider the growth rings the heavier, harder, stronger, and stiffer the wood will be.[92] Although this is generally the case, here again the quality of the summerwood must also be considered, together with the conditions under which the material was grown.

---

[91] See pages 233–5 for detailed requirements.

In the diffuse-porous hardwoods, in which the pores, or vessels, are scattered throughout the growth rings, instead of being localized in a zone in the springwood, there is apparently no very definite relation between rate of growth and strength of material. However, as with the conifers, a medium rate of growth is usually associated with stronger wood than is very fast or very slow growth.

Generalizations such as those discussed in the immediately preceding paragraphs are subject to considerable modification as a consequence of the growth history of the tree from which the wood was produced. Consequently, unless considered together with this factor, rate of growth must be regarded as having only limited value, as far as evaluation of the strength of wood is concerned.

Paul,[93] in studying southern pine, found that: "As a rule, the virgin-growth southern pines contained wood of low specific gravity in the very narrow slow-growth annual rings in the outer portions of the boles and wood of comparatively high specific gravity in the central portions representing an intermediate rate of growth. Exceptions were found in trees that had made very rapid growth in early life and as a result possessed wide rings of low specific gravity near the center. In the second-growth trees, the wood of low specific gravity was contained in the wide growth rings usually occupying the central portion of the trees. This was especially true in stands where the trees started with plenty of growing space and then crowded each other as they increased in size. The wood of medium growth rate in well-stocked second-growth stands was as heavy as the best wood from virgin-growth trees."

---

[92] Wide-ringed wood is often called *second-growth,* because the growth of the young timber in open stands after the old (virgin-growth) trees have been removed is more rapid than in trees that grew up under conditions of active competition for growing space, sunlight, and soil moisture and nutrients. *Virgin growth* is generally thought of as slow-growing timber, although individual trees in a virgin forest may have the characteristics of second-growth, and *vice versa.* In the manufacture of articles in which toughness is an important prerequisite, specifications often call for second-growth ring-porous hardwood material. This is particularly so in the selection of hickory for handles and ash for baseball bats.

[93] Benson H. Paul, *The application of silviculture in controlling the specific gravity of wood,* U. S. Dept. Agr. Tech. Bul. 168, Washington, 1930, pp. 7, 10–11, 13.

Also Benson H. Paul, Steps in the silvicultural control of wood quality, *Jour. For.,* Washington, Nov. 1946, pp. 953–8.

As a result of his study of white ash, Paul[93] made the following deductions concerning ring-porous woods, which were corroborated by his investigation of pignut and shagbark hickory:

1. "During the early life of the white ash trees studied, the rate of growth did not seem to influence the specific gravity, since wood of high specific gravity was formed whether the growth was rapid or slow.

2. "The white ash trees that maintained a nearly uniform rate of growth in diameter did not show any great differences in the specific gravity of the wood produced in different periods of their growth.

3. "A retardation of the growth of the white ash trees studied, as exhibited by the formation of narrower annual rings, produced wood of low specific gravity.

4. "An increase in the rate of growth of the white ash trees investigated, following a period of suppressed growth, produced wood of high specific gravity."

Regarding the effect of changes in rate of growth of a diffuse-porous wood within a tree due to the alteration of growing conditions during its life, Paul[93] found that in sugar maple and yellow poplar the results were essentially the same as in the ring-porous ash and hickory. The maple and poplar showed less abrupt changes in specific gravity with the first retardation of the growth rate than the ring-porous woods, but the continuation of the adverse growing conditions resulted in the formation not only of narrower rings but also of more porous wood, so that the specific gravity was correspondingly decreased (see Fig. 43). The wood produced during the initial growth periods, even though growth was slow, and the wood produced during periods of maintained or of accelerated rate of growth in diameter were the heaviest.

Position in Tree

The influence of position in tree on the strength properties of wood is usually closely related to differences in specific gravity. Variations throughout a particular cross section are generally in accord with rate of growth as previously discussed (pages 163–6). The wood in the outer portions of the cross section of mature trees of large size is, in both hardwoods and softwoods, characteristically of slow growth and accordingly light and relatively weak. In the softwoods, the wood immediately adjacent to the pith is normally lower in density and strength than that occurring somewhat farther out from the pith.

As a general rule it may be said that, except for buttressed trees or trees with swelled bases usually found growing under swampy conditions, the butt log contains wood of greater density and strength than that occurring in intermediate or top logs.[94]

In a recent study of the properties of second-growth Douglas fir, the specific gravity of wood adjacent to the pith as well as that further removed from the center of the cross section was found to decrease with increasing height above ground.[95] At any particular height the wood near the pith was consistently lighter than that occurring at some distance from the pith as shown in Fig. 44*A*. Modulus of rupture (Fig. 44*B*) and modulus of elasticity varied in a similar manner.

[94] L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935, p. 40.

Also R. F. Luxford and L. J. Markwardt, *The strength and related properties of redwood,* U. S. Dept. Agr. Tech. Bul. 305, Washington, 1932.

J. Edson Myer, *The structure and strength of four North American woods as influenced by range, habitat, and position in the tree,* N. Y. State Col. For. Tech. Publ. 31, Syracuse, 1930.

R. W. Sterns, *Canadian Douglas fir: its mechanical and physical properties,* Canada Dept. Int. For. Serv. Bul. 60, Ottawa, 1918.

J. B. Johnson and F. Roth, *Southern pine—mechanical and physical properties,* U. S. Dept. Agr. For. Serv. Circ. 12, Washington, 1896.

A. W. Brust and E. E. Berkeley, The distribution and variations of certain strength and elastic properties of clear southern yellow pine wood, *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 35, 1935, pp. 1–31.

[95] Frederick F. Wangaard and Eugene V. Zumwalt, Some strength properties of second-growth Douglas fir, *Jour. For.,* Washington, Vol. 47, Jan. 1949, pp. 18–24.

Although studies of Canadian white spruce[96] indicate that, in this species, the wood toward the tops of old trees is heavier than that formed lower in the stem, the results of numerous European observations indicate that this relationship is not characteristic of softwoods generally, nor even of the related Norway spruce of Europe, although such a trend is apparently not unusual in the latter species.[97] Wood from the lower por-

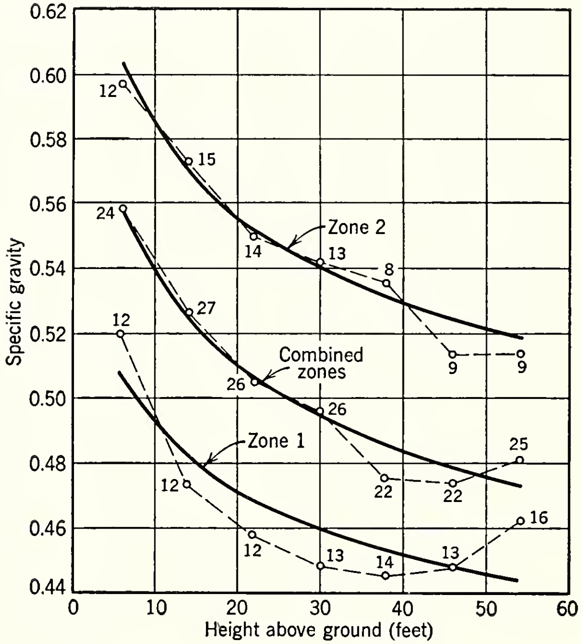


Fig. 44A

Fig. 44. Effect of position in the tree on the properties of second-growth Douglas fir. *A*. Specific gravity. *B*. Modulus of rupture.

Zone 1 extends from 1¼ to 3¾ inches from the pith.
Zone 2 extends from 3¾ to 6¼ inches from the pith.

---

[96] T. A. McElhanney and associates, *Canadian Woods: their properties and uses,* Canada Dept. Int., Ottawa, 1935, pp. 71–2.

[97] See Eric Volkert, Untersuchungen über Grosse und Verteilung des Raumgewichts in Nadelholzstämmen, *Schriftenreihe der Hermann Göring Akademie der Deutschen Forstwissenschaft,* Frankfurt, Band 2, 1941, pp. 1–133.

tions of white ash trees growing in the overflow bottomlands along the Mississippi River has been found to be of lower density than that produced in the same trees at heights of 16 feet or more. In white ash from other areas studied the wood at the base was heavier than that higher in the bole of the tree.[98]

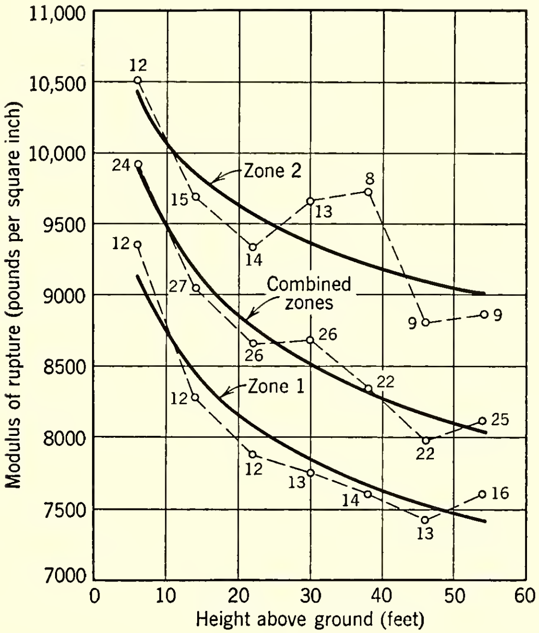


FIG. 44B

An interesting mechanical explanation of the variation in density of wood throughout the tree bole has been advanced by Volkert,[97] modifying the earlier conclusion of Metzger.[99] Metzger considered that the stem of a tree assumed the form of a beam of uniform resistance to wind loads acting on the crown. If this assumption were correct, the cube of the diameter of the bole would vary in a linear relationship with distance from the center of gravity of the crown. Volkert observed that the rate of taper of the bole is usually less than that required for such a relationship and suggested that the tree may produce wood of higher specific gravity, with correspondingly greater strength, to compensate for its lack of the required diameter in the lower portions of the bole. According to this hypothesis the ratio of the density of the wood near the base to that higher up in a tree bole would be greater in a cylindrical stem than in one that is strongly tapered.

---

[98] B. H. Paul, Influence of growth conditions upon the properties of wood, *Jour. For.*, Washington, Vol. 22, Nov. 1924, pp. 707–23.

[99] C. Metzger, Der Wind als massgebender Faktor für das Wachstum der Bäume, *Mündener forstl. Hefte,* 3, 1893, p. 35.

Age of Tree

The influence of age of tree on the strength of currently formed wood is related to many factors affecting the growth of the tree, and it is impossible to state any general relationships in this respect. Studies of the properties of the wood of a number of plantation-grown coniferous trees 25 to 35 years old have shown them to be considerably lower in density and strength properties (particularly in modulus of elasticity and maximum crushing strength) than older, forest-grown material.[100] In the study of second-growth Douglas fir previously mentioned,[95] the relationship was determined between age and specific gravity at various heights in trees selected as representative of the dominant or codominant crown classes in stands of average stocking (Fig. 45*A*). A similar relationship was found for modulus of rupture (Fig. 45*B*) and modulus of elasticity. Both density and strength of currently formed wood increased with age of tree at any particular height, but the relatively small increase shown between 60 and 80 years suggests that these properties probably "level off" after an undetermined period of years beyond the limits that were studied.

Conditions of Growth

It is evident from the nature of the production of wood that the various environmental factors concerned with the growth of trees, such as geographical distribution, elevation, air temperature, solar radiation, humidity and precipitation, soil characteristics, and growing space, may be expected to exert an influence on the

---

[100] A. Richard Olson, Nicholas V. Poletika, and Henry W. Hicock, *Strength properties of plantation-grown coniferous woods,* Conn. Agr. Expt. Sta. Bul. 511, New Haven, 1947.

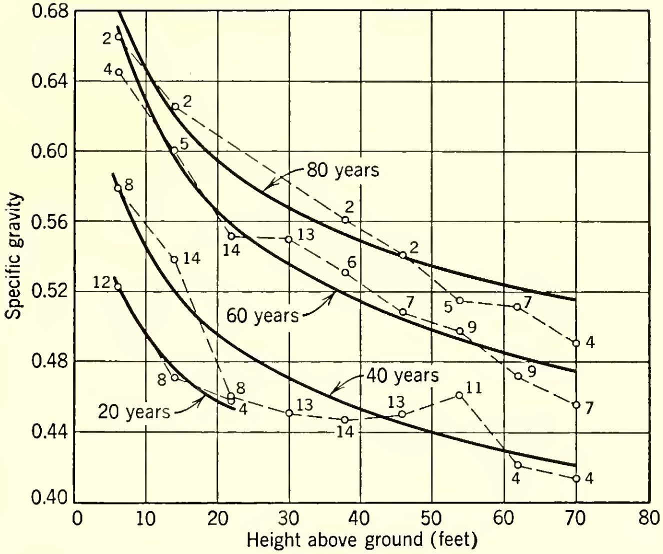


FIG. 45A

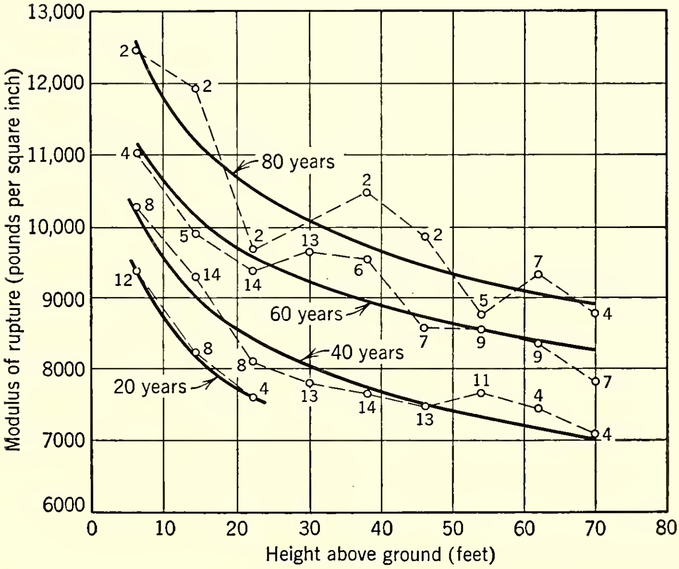


FIG. 45B

FIG. 45. Effect of age of tree on the properties of currently formed wood at various heights in the bole. (Data for second-growth Douglas fir.) *A*. Specific gravity. *B*. Modulus of rupture.

structure and chemical composition of wood and, consequently, on its technical properties.[101]

Empirical ideas concerning the effect of certain of these factors on the quality of wood have been formed as a result of experience gained in the long-continued use of the material, and the users of wood often discriminate against a species from a given region or against certain conditions of growth. For example, a marked difference is recognized between the strength of the Rocky Mountain and Coast types of Douglas fir, the latter being considered decidedly superior. Wide-ringed "second-growth" specimens of oak, ash, and hickory are almost universally acknowledged as superior in strength and toughness to "virgin-growth" pieces of these woods. Northern and Appalachian oak are generally considered of softer texture than that from the southern lowlands, and separate schedules have been found necessary for kiln-drying the two general types of wood. Further, a discrimination is also sometimes made against other southern hardwoods, as it is believed that the same kind of material from northern areas is decidedly superior in many respects.

The importance of some of the environmental factors is often overestimated, however, and sometimes the discriminations have no actual basis of fact. This is particularly true in regard to the supposed influence of geographical distribution and elevation. Comparison of data on mechanical and physical properties of yellow poplar at Yale failed to reveal any appreciable differences between material grown in Kentucky, North Carolina, Tennessee, Virginia, or Connecticut. It is only with species such as Douglas fir, which grow over a wide area characterized by distinct differences in climatic conditions, that any apparent correlation is found between quality and geographic location. As a case in point, variations in the properties of ash were found to be greater within a tree and between individual trees from the same site than were the differences in the average density of wood from high elevations in the Appalachian Mountains and the overflow regions of the Mississippi River.[102] In this particular case, the only feature that could be attributed directly to the influence of locality was found in wood from the lower portions of white ash trees growing in the overflow bottomlands along the Mississippi River.

---

[101] For discussion of factors involved in the study of this problem see Arthur Koehler and Benson H. Paul, *Discussion of research on the relation of growth factors to the quality of wood produced in forest trees,* For. Prod. Lab. Mimeo. Rept., Madison, 1929.

[102] Paul, footnote 98.

A prejudice exists against the use of hickory from the Appalachian Mountains for exacting strength purposes, but tests have shown that a high percentage of hickory from this section compares favorably with that from other regions.[103] The quality of the Appalachian timber is admittedly variable, but judicious selection of material should make available a considerable quantity of desirable hickory. Even in Douglas fir, although actual mechanical tests bear out the general preference for the Coast type as far as *average* strength values are concerned, it is largely a matter of percentage and size of trees that makes that type more suited than Rocky Mountain Douglas fir. There is more timber of structural quality in the West Coast area than in the Rocky Mountains, but, since both very strong and very weak specimens of the same species are to be found within any large district, one is not justified in condemning all the Rocky Mountain type. In general, it may be said, from the point of view of strength, that the various factors of growth are of practical importance only as far as they affect the density of the wood. In any case, the density of the material should be taken as the final criterion of its strength, regardless of where it may have been produced.

Table 11 showing the probable variation in a number of properties of a random tree from the average for a species is generally applicable over the commercial range of a species.

Study of the effect of the various conditions of growth on the properties of wood has been carried on in Europe for some time, but it has only been within the past thirty years that such investigations have been made in the United States on a comprehensive scale.[104] Outstanding among the investigations made abroad are those of Robert Hartig,[105] who evolved what he termed the

---

[103] B. H. Paul, The quality of Appalachian hickory, *Southern Lumberman,* Nashville, Vol. 135, Apr. 6, 1929, pp. 29–32.

[104] A list of references pertaining to these various researches has been compiled by Koehler and Paul in the mimeographed report previously cited, footnote 101.

[105] R. Hartig, *Holzuntersuchungen, Altes und Neues,* Berlin, 1901.

TABLE 11. PROBABLE VARIATION IN STRENGTH OF RANDOM TREE FROM AVERAGE FOR SPECIES *

Property	Percent
Specific gravity based on volume when green	4
Static bending:	
Fiber stress at proportional limit	9
Modulus of rupture	7
Modulus of elasticity	9
Work to maximum load	15
Impact bending:	
Fiber stress at proportional limit	8
Work to proportional limit	12
Height of drop	13
Compression parallel to grain:	
Fiber stress at proportional limit	12
Crushing strength	7
Compression perpendicular to grain: Fiber stress at proportional limit	14
Hardness:	
End	10
Side	9
Shearing strength parallel to grain	7
Tension perpendicular to grain	12

* From L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935.

"nourishment" theory (*Ernährungs Theorie*), in which he contended that the quality of wood is dependent on the relation existing among soil fertility, transpiration of water by the crown of the tree, and assimilation. He asserted that the density of the wood is influenced by the ratio of amount of conducting tissue to supporting tissue; consequently, the greater the transpiration compared with the production of wood substance, the greater the volume of porous, conducting tissue formed and the lighter the wood. On the other hand, denser wood is formed when normal transpiration is accompanied by rapid assimilation.

In the United States the investigations of Paul,[106] carried on since 1922, have been most comprehensive. Working with white ash, pignut and shagbark hickory, rock elm, sugar maple, yellow poplar, southern pine, and second-growth redwood, Paul arrived at the following conclusions regarding the influence of growing conditions on the quality of wood:

[106] Paul, footnote 93.

1. "The regulation of growing space is the silvicultural tool which the forester can use most easily in controlling the specific gravity of wood. The species studied showed a ready response to changes in the condition of the stand, whether it be crowding or thinning.

2. "In all of the broad-leaved species investigated severe crowding in the stands resulted in a decrease in the specific gravity of wood, while relief from crowding was always accompanied by an increase in specific gravity.

3. "Wood having the most uniform properties and the highest quality with respect to both strength properties and freedom from defects is produced, in the hardwoods, when the trees are grown sufficiently close together while young to cause removal of lateral branches, and are subsequently thinned sufficiently to maintain or increase the rate of diameter growth of the trees.

4. "Where dry sites or soils low in fertility are involved, the silvicultural treatment (of hardwoods) should also aim to benefit the water-holding capacity and the fertility of the soil.

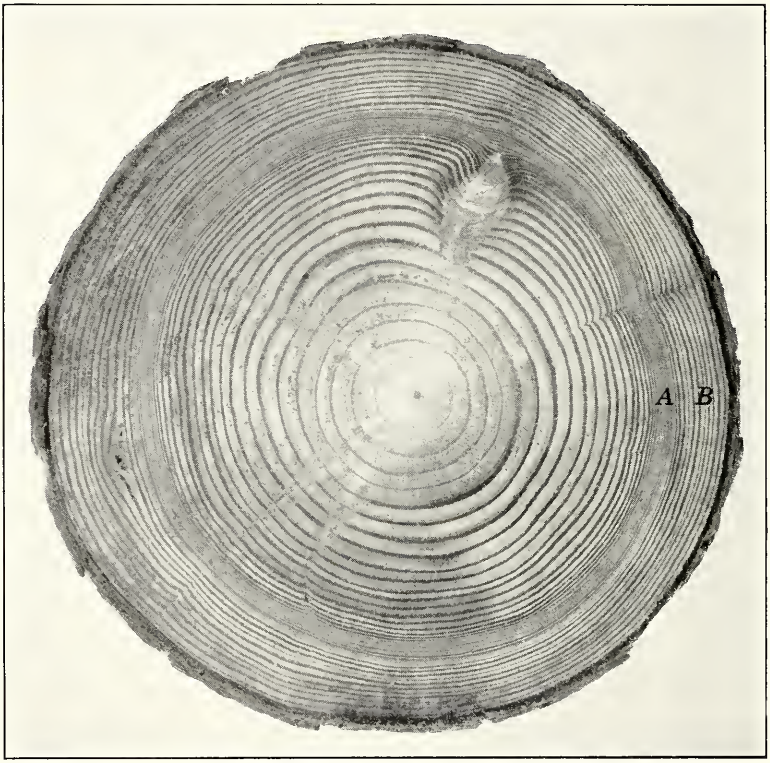
5. "During the early years of the coniferous stands studied the size of the individual tree crown appears to be the principal factor in determining the specific gravity of the wood.

6. "The young southern pine and redwood trees with large crowns growing in fairly open stands produced greater amounts of springwood than summerwood in the annual rings, while trees of similar age with small crowns growing in fairly dense stands produced more nearly equal amounts of springwood and of summerwood.

7. "Where crowding in a southern pine stand had resulted in a decline in the specific gravity of the wood, a thinning either caused a subsequent increase in rate of growth in diameter accompanied by a remarkable increase in specific gravity when all of the growth conditions in the stand were especially favorable, or such a thinning caused a decrease in the specific gravity of the wood when the growth conditions were apparently more favorable to the production of springwood than summerwood (see Figs. 46 and 47).

8. "The closely crowded trees on the good sites continued to produce wood of high specific gravity under conditions of crowding that greatly reduced the growth rate. In such trees the proportion of summerwood was relatively high.

9. "Heavy wood in the open stands of southern pine was produced when the conditions of soil moisture and of soil fertility were such that the trees continued to grow throughout the vegetative season sufficiently to maintain a high proportion of summerwood in the annual growth rings.



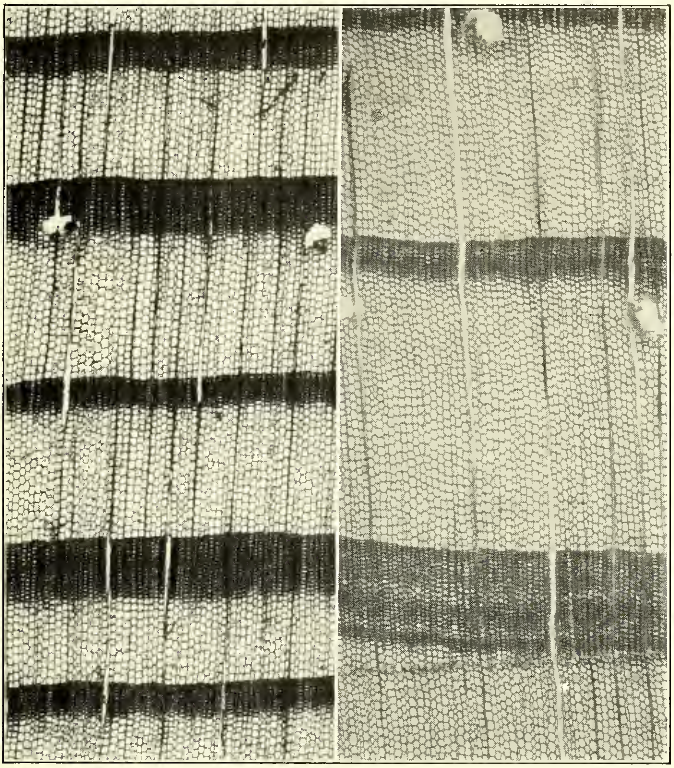
Forest Products Laboratory Photo

Fig. 46. Cross section of shortleaf pine tree showing (*A*) restricted growth during a period of crowding, and (*B*) subsequent increase in growth following the removal of some of the surrounding trees.

10. "The second-growth shortleaf pine growing on a very dry site produced wood of much lower specific gravity than that of the other second-growth shortleaf pine stands investigated.

11. "In coniferous species, such as the southern pines and redwood, the control of specific gravity by the influence of growing space must be dealt with somewhat differently than in the broad-

leaved species. In order to produce timber of high strength in the shortest possible time it will be necessary to thin the stands carefully, to prevent forest fires, and to maintain as good soil conditions as possible during the life of the stand. Thus, quantity and quality production are apparently combined on the more fertile sites.



Forest Products Laboratory Photo

FIG. 47. Cross sections of shortleaf pine showing the structure of wood formed during the period of moderately slow growth (*left*) and the later period of more rapid growth (*right*) in the tree illustrated in Fig. 46. ×17½. In this case the specific gravity of the wood formed after the thinning is slightly lower than that formed during the period of slower growth.

12. "To produce light wood in second-growth southern pines and redwood, relatively wide spacing of the trees throughout the entire period of growth is required. The individual trees will

then have larger crowns, more knots, shorter clear boles, and a higher percentage of sapwood, but to offset these disadvantages it will be possible to grow a tree of specified diameter in a much shorter time."

Microstructure of Wood

Aside from their effect on the density of wood, growth conditions may affect the strength of wood through their influence on the character of the cellular structure of wood, the structure of the cell wall, or even on the composition of wood substance itself. Little evidence has been accumulated to indicate the degree to which variations in proportion among various types of cells may affect the strength of wood of comparable density. Although many investigators have attempted to correlate fiber length with strength properties, no relationship in this respect has been found. Studies of the microscopic and submicroscopic structure of the cell wall have been more successful in explaining the basic causes of variation in the strength properties of wood.

Among the various characteristics that have been examined is the orientation of the fibrils that compose the principal portion of the secondary cell wall. Varying degrees of correlation have been indicated between fibril angle and the strength and elastic properties of wood.[107] Modulus of rupture, tensile strength parallel to grain, modulus of elasticity, and maximum crushing strength decrease as the orientation of the fibrils deviates from the longitudinal axis of the wood. Attention has been called to the greater fibril angle (as measured from the longitudinal axis) in springwood tracheids, compared with summerwood tracheids of conifers, and the brashness of springwood has been attributed at least in part to this factor. According to Koehler,[108] "Springwood of softwoods . . . is weaker than summerwood for three reasons: (1) the relatively small amount of wood substance present, as evidenced by the thin cell walls and the large cell cavities, (2) the relatively large slope of the fibrils in the secondary wall, and (3) the presence of a relatively greater proportion of the middle lamella and the immediately adjoining layer with their presumably lower tensile strength." In the wood of young softwood trees, at least, a large fibril angle is associated with rapid growth and is believed to be responsible for the low-strength properties of such material in relation to its density.

---

[107] Hereford Garland, A microscopic study of coniferous wood in relation to its strength properties, *Ann. Missouri Bot. Gard.,* St. Louis, Vol. 26, 1939, pp. 1–94.

Also Pillow and Luxford, footnote 51.

F. Kollmann and M. Antoneff, Beitrag zur Erforschung des submikroskopischen Feinbaus von Holz, *Holz,* Vol. 6, 1943, pp. 41–5.

John Hugo Kramer, *Growth-strength relations of red pine,* Unpubl. doctorate dissertation, Yale School For., New Haven, 1943.

[108] Koehler, footnote 45, p. 17.

In addition to the orientation of structural units in the cell wall, there is some evidence that variation in chemical composition, particularly in the proportion of lignin and cellulose, may also be a factor affecting the mechanical properties of wood.[109]

Moisture Content

By the **moisture content** of wood is meant the weight of the water contained in the material, expressed as a percentage of the oven-dry weight.[110] For example, if the weight of a specimen of wood, before drying, is 130 grams and after oven drying is 100 grams, it is said to contain 30 percent moisture. That is, the moisture content is the difference between the original and oven-dry weights (which represents the weight of contained moisture) divided by the oven-dry weight. This is expressed as a percentage by multiplying by 100.

---

[109] H. E. Dadswell and L. F. Hawley, Chemical composition of wood in relation to physical characteristics—a preliminary study, *Ind. and Eng. Chem.,* Washington, Vol. 21, 1929, pp. 973–5.

Also S. H. Clarke, *The toughness of timber,* For. Prod. Res. Lab. Proj. 18, Proj. Rept. 9, Great Britain, 1938.

[110] Moisture content is determined as described under Timber Testing, page 280.

Even oven-dry wood contains a trace of moisture, but, for all except chemical purposes, it may be considered absolutely dry. A number of woods, such as the pines and cedars, contain resins, oils, or other extraneous materials that are volatile, at least in part, at 100°C., the temperature at which specimens are usually dried in making moisture determinations. Consequently, the apparent moisture content of specimens of these woods may be greatly influenced by the amount of such volatile substances removed in drying the pieces. A method of determining the actual moisture content of such woods is discussed on page 281. See E. Bateman and E. Beglinger, Experiments on the determination of moisture in wood by laboratory methods, *Proc. Am. Wood Pres. Assn.,* Chicago, 1929, pp. 193–201; also Rept. of Comm. 8–3, Moisture content determination, *Ibid.,* pp. 180–93.

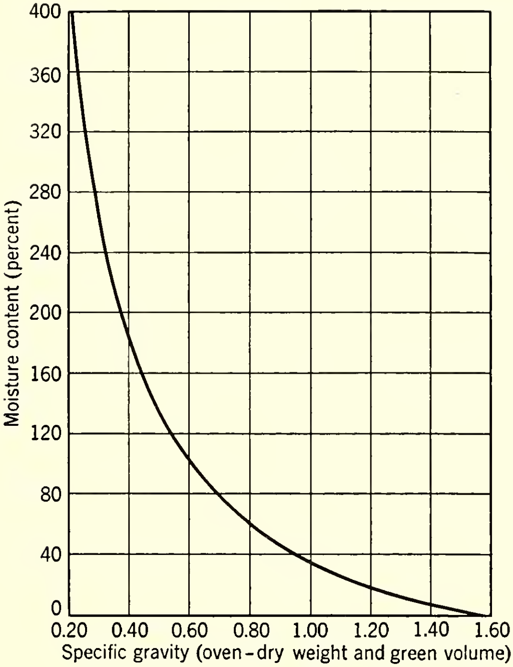
There is a wide variation in the amount of moisture contained in the unseasoned wood of the various species of living trees. Among the hardwoods, white ash and black locust are comparatively dry, averaging about 40 percent moisture, whereas basswood and chestnut are relatively wet, containing over 100 percent. A similar variation is found among the conifers, western red cedar and Douglas fir averaging less than 40 percent, whereas such woods as incense cedar, balsam and white fir, eastern hemlock, sugar pine, and Engelmann spruce contain 100 percent or more moisture on the average (see Table 1).

Most of the hardwoods show a fairly uniform distribution of moisture between heartwood and sapwood in unseasoned timber, but in certain of the conifers the sapwood is decidedly more moist, in many cases approaching the maximum attainable for wood of a particular specific gravity as shown in Fig. 48. Thus, in southern yellow pine, the moisture content of the sapwood is usually in excess of 100 percent, whereas the heartwood ranges from 30 to 40 percent. It is evident that, in species characterized by such a distinct difference, the weight of unseasoned wood may vary over wide limits, depending on the proportion of sapwood contained in it. In some coniferous trees there is also a pronounced variation in the moisture content of the heartwood itself, that at the base being decidedly more moist than the comparatively dry heartwood higher up in the tree. This proved to be the case in redwood, in which the moisture content of the heartwood was found to decrease gradually from an average of approximately 150 percent at the base to about 60 percent at a height of 80 feet; above this point the moisture remained practically constant.[111]

The moisture content of "air-dry" wood in service varies over rather wide limits, depending on the climate, period of seasoning, and the size and form of the piece. The species may also be a factor, especially when relatively short seasoning periods are involved, since the various woods differ markedly in the rate at which they give up their moisture when subjected to drying conditions, as well as in the rate at which they absorb moisture during damp or wet weather. If material 2 inches or less in thickness is protected from rain and snow and not exposed to artificial heating, it will eventually reach a moisture content that is in equilibrium with the surrounding atmospheric conditions. In most sections of the United States this represents an average of about 12 percent moisture. For this reason, strength values for air-dry woods are usually adjusted to 12 percent moisture content even though the test specimens may be somewhat below or above that degree of dryness. Climatic conditions in the Gulf States and on the West Coast are such that thoroughly air-dry material may have a moisture content of 15 to 18 percent, whereas in the arid Southwest it is usually nearer 10 percent.

---

[111] R. F. Luxford, Distribution of moisture in virgin redwood trees, *Timberman*, Portland, Oreg.; Vol. 31, Feb. 1930, p. 106.



Forest Products Laboratory Data

FIG. 48. Relationship between specific gravity of wood and its moisture content when completely saturated. The fresh sapwood of many species approaches the saturation moisture content.

The amount of moisture contained in a piece of wood has an important bearing on its weight, but, when the moisture content of comparatively dry wood changes, the weight per cubic foot does not change so much as might be expected. This is due to the fact that, as dry wood takes on moisture, the weight tends to increase because of the added water, while at the same time its volume also tends to increase since the resultant swelling causes the wood substance to occupy a greater space. Conversely, the further drying of the material decreases both its weight and volume. A rule of thumb for estimating changes in the weight per cubic foot of wood at a moisture content near 12 percent is to consider a ½ percent change in weight as accompanying a 1 percent change in moisture. Thus, wood at 8 percent moisture content weighs about 2 percent less per cubic foot than at 12 percent, whereas at 14 percent the weight is about 1 percent greater than at 12 percent.[112]

Large timbers season very slowly and may have a higher moisture content, even after long periods of seasoning, than thinner material; also the moisture will likely be unevenly distributed throughout the cross section of the pieces. Tests made by the Forest Service on yellow pine bridge stringers, some 12 by 12 inches in cross section and others 8 by 16 inches, showed that after two years of seasoning the average moisture content of the exterior shell extending halfway to the center was 18 percent, whereas that of the remaining interior was 25.7 percent. Redwood timbers, 8 by 16 inches in cross section, averaged 17 percent in the outer portions and 33 percent in the inner core after seasoning for 20 months.[113]

Kiln-dried wood exhibits a wide variation in moisture content, depending on the use to which the material is to be put. For exacting uses, where a low moisture content is essential, as in furniture, cabinet work, interior finish and flooring, and in airplane parts, it is usually appreciably below that of thoroughly air-dried material. For other forms of wood, such as sheathing, roof boards, and framing, kiln drying is often resorted to merely to remove the bulk of the moisture in a relatively short time, and the moisture content may vary from 10 to 25 percent or more.

---

[112] L. J. Markwardt, *Comparative strength properties of woods grown in the United States*, U. S. Dept. Agr. Tech. Bul. 158, Washington, 1930, p. 20.

[113] Arthur Koehler and Rolf Thelen, *The kiln drying of lumber,* McGraw-Hill Book Co., New York, 1926, p. 36.

RELATION OF MOISTURE CONTENT TO STRENGTH OF WOOD[114]

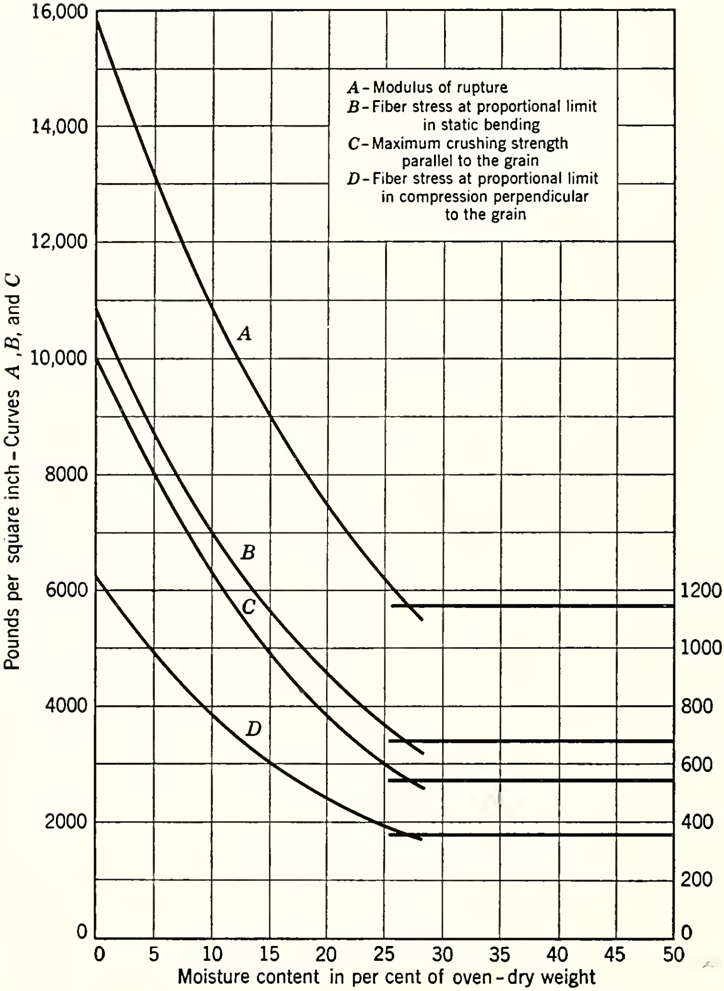
As explained in the discussion of checks as defects (page 83), when wood is dried below the fiber-saturation point, the walls of the individual cells become more and more compact. The fibers consequently become stronger and stiffer, and, as a result, a decrease in moisture content is accompanied by an increase in most of the strength properties of clear wood. Above the fiber-saturation point changes in moisture content have no apparent effect on the strength of the wood. Small clear specimens of wood in a thoroughly air-dry condition (12 percent moisture) have practically twice the strength in bending and endwise compression of the same material when unseasoned, whereas, when the material is kiln-dried (to approximately 5 percent moisture), the increase in strength may be threefold. The relation between the moisture content and the strength of the wood of Sitka spruce is shown in Fig. 49.

That the changes in the different strength properties are not the same for given changes in moisture content is indicated in Fig. 49, as well as in Table 12, which shows the approximate variation in strength with a 1 percent change in moisture below the fiber-saturation point. Since the increase in strength accompanying loss of moisture is an exponential relationship, as shown in Fig. 49, these percentage values should be applied successively for each 1 percent change in moisture content in arriving at the increase in strength resulting from a moisture content decrease of several percent. From Table 12 it may be seen that strength as a beam (modulus of rupture) and as a column (maximum crushing strength in endwise compression) is increased to a marked extent as the wood becomes drier, whereas stiffness (modulus of elasticity) is influenced to a lesser degree by such moisture changes. An exception to the general rule that the strength of clear wood increases appreciably as the moisture content decreases is observed in the properties related to toughness. Both work to maximum load in static bending and height of drop of hammer necessary to produce complete failure in impact bending change only slightly as the moisture content decreases. This condition is explained by the fact that toughness involves pliability as well as strength. Although dry wood will support a greater load than unseasoned material, it will not bend so far

---

[114] For further discussion see T. R. C. Wilson, *Strength-moisture relations for wood,* U. S. Dept. Agr. Tech. Bul. 282, Washington, 1932.

Also T. R. C. Wilson, T. A. Carlson, and R. F. Luxford, The effect of partial seasoning on the strength of wood, *Proc. Am. Wood Pres. Assn.,* Chicago, 1930, pp. 349–78.



Forest Products Laboratory Data

FIG. 49. Relation between strength and moisture content of small clear specimens of Sitka spruce.

before failure occurs. The results of shearing tests are erratic and often fail to show such an appreciable increase in strength on drying as is indicated in Table 12, probably owing to the development of small checks. The percentage change in strength that results with given changes in moisture content varies with the different species and also with different specimens of the same species. Redwood, for example, is increased somewhat less in strength by seasoning than most other woods.

TABLE 12. AVERAGE INCREASE IN VALUE OF VARIOUS STRENGTH PROPERTIES AFFECTED BY DECREASING MOISTURE CONTENT 1 PERCENT*

Property	Percent
Static Bending	
Fiber stress at proportional limit	5
Modulus of rupture (bending strength)	4
Modulus of elasticity (stiffness)	2
Work to proportional limit	8
Work to maximum load (shock-resisting ability)	½
Impact Bending	
Fiber stress at proportional limit	3
Work to proportional limit	4
Height of drop of hammer causing complete failure	−½
Compression Parallel to Grain	
Fiber stress at proportional limit	5
Maximum crushing strength	6
Compression Perpendicular to Grain	
Fiber stress at proportional limit	5½
Hardness, end grain	4
Hardness, side grain	2½
Shearing strength parallel to grain	3
Tension perpendicular to grain	1½

* From U. S. Dept. Agr. Tech. Bul. 479, p. 51.

In view of the influence of moisture content, when below the fiber-saturation point, on the strength of small clear specimens of wood, it is essential that tables of strength values, derived from tests on such material, either indicate the moisture content of the test specimens or be adjusted to a given moisture content. In tabulating results for air-dried material the latter procedure is customary, the values being adjusted to 12 percent moisture content. For this purpose the equation derived by Wilson[115] provides the most accurate method of adjustment. This equation is usually written

---

[115] Wilson, footnote 114.

$$\log S_D = \log S_C + \frac{(C - D) \log \dfrac{S_B}{S_A}}{A - B} \tag{10}$$

in which A, B, C, and D are moisture content values, and S_A, S_B, S_C, and S_D are corresponding strength values. This equation is that of a straight line ($y = b + ax$), and its use is based on the fact that moisture-content values below the fiber-saturation point and the logarithms of corresponding strength values show a straight-line relationship. By substituting average green and air-dry strength values for a particular species from Tables 1 and 2 for S_A and S_B in the equation, together with appropriate values for A and B, it is a simple matter to adjust a strength value (S_C) at C percent moisture content to its equivalent (S_D) at the desired moisture content (D). As indicated previously, the common moisture content to which air-dry specimens are adjusted is 12 percent. In using green strength values from Table 1 for S_A, it is important to use the value for A corresponding to the fiber-saturation point, above which strength is constant. This moisture-content value is commonly assumed to be 24 percent except for the following:

	Percent
Birch, yellow	27
Hemlock, western	26
Larch, western	28
Pine, loblolly	21
longleaf	21
Redwood	21
Spruce, red	27
Sitka	27

Application of equation 10 may be illustrated by adjusting the maximum crushing strength of a specimen of hard maple, determined as 10,300 pounds per square inch based on tests at 9.5 percent moisture content, to 12 percent moisture content.

Then $B = 12$ $S_B = 7830$ (Table 2)
$A = 24$ $S_A = 4020$ (Table 1)
$C = 9.5$ $S_C = 10{,}300$
$D = 12$ $S_D = ?$

$$\log S_{12} = \log 10{,}300 + \frac{(9.5 - 12)\log \dfrac{7830}{4020}}{24 - 12}$$

$S_{12} = 8960$ pounds per square inch and is the maximum crushing strength for this specimen adjusted to 12 percent moisture content.

All methods for the adjustment of strength for differences in moisture content are based on the assumption that moisture distribution is uniform throughout the specimen. Preference is often given, when possible, to testing wood in the unseasoned condition, since, no matter how wet the wood may be, there is no apparent change in strength, and correction for moisture content consequently does not have to be considered.

The strengthening effect of drying, however, although often very marked in small clear specimens, may be entirely offset in larger pieces by the development of checks and other defects during seasoning. This is particularly true in the lower grades of structural material, owing to the prevalence of checking in and around knots. As a result, the lower grades of large timbers and about 25 percent of the higher grades show no increase in strength with drying, although the average strength of such timbers is increased slightly.

Effect of Method of Drying on Strength

The method of drying may have a pronounced effect on the strength of wood, depending on the extent to which seasoning defects are developed. In many quarters there is a common belief that kiln-dried wood is inferior in strength to air-dried material. In some instances, where wood has been kiln dried under unfavorable conditions of temperature and humidity, the strength may be considerably reduced as a result of checking, the development of severe internal stresses (as in casehardening) and chemical changes in the wood. Checking and even casehardening may also occur in air drying, and in certain species little can be done to control them effectively. With proper kiln drying, however, the seasoning injuries can be reduced to a minimum, if not entirely avoided, in all woods, and material so dried is fully equal in strength properties to air-dried stock of the same quality and moisture content. This is borne out by the results of over

100,000 mechanical tests made by the Forest Products Laboratory in connection with the kiln drying of wood for airplane construction.[116] These tests showed further that the strength properties of wood, particularly toughness or resistance to shock, may be quite seriously reduced under certain drying conditions without any visible evidence of such injury.

Another reason for the prejudice against kiln-dried wood is found in the manner of failure, since very dry wood fails more abruptly and with less bending than material of a higher moisture content. However, although inclined to be more brittle, the drier piece is capable of supporting a greater load, unless it has been dried under very unfavorable conditions.

The relation of moisture content to the strength of clear wood does not hold when very dry wood is allowed to reabsorb moisture. A piece of wood dried to 3 or 4 percent and then exposed to atmospheric conditions which cause an increase to 15 percent moisture content is somewhat weaker and more brittle than a similar piece that has never been dried below 15 percent.[117] The same effect is produced when dry wood is soaked in water, such material being somewhat less resilient than it was in the original unseasoned condition.

Temperature

The effects of temperature on the strength and elastic properties of wood may be classified as temporary or permanent. Temporary effects are those that exist only at the particular temperature involved and are independent of the period of exposure to high or low temperatures. Permanent effects are those that are retained after the wood has been restored to normal temperature and are a function of duration of temperature as well as temperature itself.

Several investigators have studied the temporary influence of high or low temperatures on wood properties, and the effects of temperatures as low as −320°F. and as high as 400°F. have been observed.[118] Most strength properties (toughness or shock resistance is an exception) decrease at temperatures above normal room temperatures and show a corresponding increase at reduced temperatures. In general, variation in strength and elastic properties follows a linear relationship with temperature, although the degree of change appears to depend on specific gravity and moisture content. Over a wide range of temperature, Kollmann[119] has reported a change in crushing strength of approximately 100 pounds per square inch for each 6°F. temperature change for wood of 0.40 specific gravity and of 100 pounds per square inch for each 3°F. change for wood with a specific gravity of 0.80. Sulzberger's findings[118] indicate that the percentage increase or decrease in several strength properties, including maximum crushing strength, modulus of rupture, and modulus of elasticity, resulting from change in temperature is fairly constant. He found changes in these properties ranging from about 2.5 to 5 percent for each 10°F. change in temperature for a number of species tested at 15 percent moisture content.

---

[116] T. R. C. Wilson, *The effect of kiln drying on the strength of airplane woods,* Nat. Advis. Comm. Aero. Rept. 68, Washington, 1920.

Also Markwardt and Wilson, footnote 94, p. 57.

[117] Koehler and Thelen, footnote 113, p. 276.

The moisture content of wood is particularly important in its effect on strength at temperatures below the freezing point. In comparing the stiffness of wood at −58°F. with that at room temperature, Kollmann[119] has shown no change in modulus of elasticity for oven-dry wood, a 20 percent increase at the low temperature for wood at 20 percent moisture content, and proportionate increases at intermediate moisture conditions. Static-bending properties at low temperatures are similarly affected by moisture content. The modulus of rupture of moisture-saturated wood is reported by Kollmann to be about twice as great when the wood is frozen as at room temperature. Air-dry wood might be expected to increase in modulus of rupture by less than 20 percent under a comparable temperature change. The impact strength of saturated frozen wood is considerably less than that of dry wood.

---

[118] Franz Kollmann, Vorgänge und Änderungen von Holzeigenschaften beim Dämpfen, *Holz als Roh—und Werkstoff,* Berlin, Vol. 2, No. 1, 1939, pp. 1–11.

Also Franz Kollmann, Die mechanischen Eigenschaften verschieden feuchter Holzer im Temperaturbereich von −200 bis +200°C. *V.D.I. Forschungsheft* 403, (B) (11) July–Aug. 1940, pp. 1–18.

H. O. George, *The effect of low temperature on the strength of wood,* N. Y. State Col. For. Tech. Publ. 43, Syracuse, 1933.

P. H. Sulzberger, The effect of temperature on the strength of wood, plywood, and glued joints, *Jour. Coun. Sci. and Ind. Res.,* Australia, Vol. 16, No. 4, Nov. 1943, pp. 263–5.

[119] Footnote 118, Kollmann, reference 2.

The work of Greenhill[120] dealing with the influence of temperature and moisture content on properties in tension perpendicular to the grain is of especial interest from the standpoint of the fundamental nature of the stresses developed in kiln drying. At 180°F. the tensile strength and modulus of elasticity across the grain were reduced to one-third to one-half the values for corresponding properties at normal atmospheric temperature. At low moisture content the reductions with temperature increase were much less striking.

When wood is exposed to sufficiently high temperatures, certain permanent changes are brought about in the wood substance which, in turn, affect the strength of the material. The permanent influence of high temperatures on the properties of wood has been studied recently by MacLean.[121] His findings, based on tests of thin wood specimens of several species, show that properties indicative of shock resistance (toughness and work to maximum load in static bending) are much more sensitive to the deteriorating effects of heating than are modulus of rupture or modulus of elasticity.

None of the properties of wood were affected when tested at room temperature after heating in an oven at 320°F. for ½ hour, and, even after heating at this temperature for 16 hours, toughness and work to maximum load were the only properties that showed more than a slight decrease. Following the latter treatment, shock-resistance properties were reduced to about 50 to 80 percent of comparable values for control specimens. Deterioration is more rapid when wood is heated in saturated steam than in dry air at the same temperature. Heating in steam at 320°F. for 4 hours reduced work to maximum load to about 50 percent of control values, whereas the same period of heating in an oven at 320°F. produced no marked reduction in strength.

Much lower temperatures may seriously affect strength properties if the heating period is of long duration. Eleven months' exposure to an air temperature of 215°F. reduced work to maximum load to 26 percent of original, modulus of rupture to 55 percent, and modulus of elasticity to 83 percent. Immersion in boiling water for periods up to 64 hours had relatively little permanent effect on mechanical properties, and the practice of steaming or soaking wood in boiling water for short periods to improve its pliability for bending to sharp curvature has, in itself, only a minor damaging effect on its subsequent properties. (The strength of bent-wood products such as furniture parts and boat frames is, of course, dependent on the degree of overstressing involved in producing the desired curvature.) The specific effects of various methods and periods of heating on shock resistance, discussed in the preceding paragraphs are based largely on tests of Douglas fir. These relationships are believed to hold in a general way for all woods, but individual species may be affected somewhat more or less than Douglas fir under comparable conditions of heating.

---

[120] W. L. Greenhill, Strength tests perpendicular to the grain of timber at various temperatures and moisture contents, *Jour. Coun. Sci. and Ind. Res.*, Australia, Vol. 9, No. 4, 1936, pp. 265–76.

[121] J. D. MacLean, *Effect of heat on the properties and serviceability of wood: experiments on thin wood specimens,* For. Prod. Lab. Rept. R1471, Madison, 1945.

Earlier work by Koehler and Pillow[122] similarly indicated that toughness is more subject to reduction than other properties, such as specific gravity and maximum crushing strength, as a result of exposure to high temperature. A tendency toward an increasing frequency of brash failures in white ash (but not in Sitka spruce) between 2 and 8 days of heating at 280°F. was noted by these investigators.

Although the most outstanding permanent effect of high temperature is a reduction in shock-resisting ability, other properties such as bending and compressive strengths of wood may be noticeably affected if heating is continued for a sufficiently long period.

Preservative Treatment

Numerous investigations have been made from time to time by various agencies to determine the effect of standard preservatives and preservative treatments on the strength of wood.[123] The results of these tests indicate that any weakening of wood during treatment is due to the method of preparation or impregnation rather than to the preservative used. Creosote does not exhibit any chemical reaction on the wood and, hence, is not injurious. Zinc chloride is also virtually inactive in the relatively weak solutions (2 to 4 percent) used in commercial practice, although the presence of the salt in the wood apparently makes it somewhat brittle under impact. In high concentrations and at high temperatures, however, zinc chloride is capable of disintegrating the wood substance. Pentachlorophenol, copper naphthenate, and other standard preservatives have no known injurious effects on the properties of wood.

---

[122] A. Koehler and M. Y. Pillow, Effect of high temperatures on the mode of fracture of a softwood, *Southern Lumberman,* Nashville, Vol. 121, Dec. 19, 1925, pp. 219–21.

M. Y. Pillow, Effect of high temperatures on the mode of fracture and other properties of a hardwood, *Southern Lumberman,* Nashville, Vol. 137, Oct. 15, 1929, pp. 58, 60.

Most of the weakening of wood that accompanies preservative treatment can be attributed to the high temperatures often used in order to obtain satisfactory impregnations of the preservatives.[124] This is particularly true when excessive temperatures are maintained for long periods in conjunction with relatively high pressures, as is frequently the case in treating woods that are difficult to impregnate satisfactorily.

The detrimental effect of a given preservative treatment is also dependent on the kind of wood and, to some extent, on the form of material. Douglas fir is reputed to be injured more than other woods that are commonly treated because of its marked resistance to impregnation. However, there is evidence that southern pine is also seriously injured by the very severe treating conditions (preliminary steaming) to which that wood is often subjected. Poles and piling are less often damaged in treatment than sawed pieces, owing to the presence of a larger proportion of sapwood which is less refractory. Furthermore, poles are less frequently weakened than piling, since the absorption required is usually not so great, and the treatments are accordingly less severe.[125]

---

[123] For a partial list of references on the various tests conducted in this country, see Mechanical properties of treated wood, Rept. of Comm. on Properties of Treated Wood, *Proc. Am. Wood Pres. Assn.*, Chicago, 1923, pp. 361-2.

See also George M. Hunt and George A. Garratt, *Wood preservation,* McGraw-Hill Book Co., New York, 1938, pp. 306–11.

T. R. C. Wilson, Effect of creosote on strength of fir timbers, *Timberman,* Portland, Oreg., Vol. 31, June 1930, pp. 50–2, 54–6.

[124] H. S. Betts and J. A. Newlin, *Strength tests of structural timbers treated by commercial wood-preserving processes,* U. S. Dept. Agr. Bul. 286, Washington, 1915.

Prior to the actual injection of the preservative, wood is often subjected to a preliminary treatment, in order to remove part of the contained moisture, if unseasoned, and otherwise to prepare it for the subsequent impregnation. Two such preliminary processes are commonly used, namely, steaming under pressure, with temperatures often as high as 259°F. (20 pounds pressure), and boiling under vacuum, with temperatures normally below 200°F. A third process, boiling at atmospheric pressure, frequently used in the past, has been very largely discontinued at the present time. Primarily because of the relatively low temperature involved, it is to be expected that the boiling-under-vacuum process will have the least deteriorating effect on wood. This is borne out by Table 13, which summarizes the results of tests made on treated Douglas fir by the U. S. Forest Service and other agencies. This table indicates that, in general, the steaming and boiling-at-atmospheric-pressure processes, in which temperatures well above 200°F. are used, reduce the strength of the wood more than the boiling-under-vacuum process with average temperatures of about 190°F., providing the duration of the treatment is the same. With any given treatment, the extent of the damage will depend, of course, on the actual temperature used, the period of exposure, and the species involved. Strength tests of clear specimens of shortleaf and slash pine sapwood after various periods of steaming revealed the losses in strength shown in Table 14 and confirm the relatively large losses in strength resulting from steaming.[126]

A second and less important cause of strength loss in treated wood is the use of excessive pressure in impregnating preservative into wood that has been softened by heating.

In order to obtain adequate penetration and uniform absorption, Douglas fir cross ties are commonly incised or perforated on the surface to the depth of penetration desired. A similar practice has been followed with western red cedar and northern

---

[125] Rept. of Comm. on Properties of Treated Wood, footnote 123, pp. 359–60.

[126] Stanley J. Buckman and Louis W. Rees, Effect of steaming on the strength of southern yellow pine, *Proc. Am. Wood Pres. Assn.*, Chicago, 1940, pp. 331–60.

TABLE 13. SUMMARY OF TESTS ON TREATED DOUGLAS FIR TIMBERS*

Series‡	Treating Process	Summary of Treatment							Ratio of Treated to Untreated Wood†	
		Temperatures		Duration of Treatment		Maximum Pressure, Psi	Pressure Period		Unseasoned, %	Seasoned, %
		Maximum, °F.	Average, °F.	Hr.	Min.		Hr.	Min.		
A1	Boiling (atmospheric pres.)	215	211	29	00	150	1	47	69.1	72.5
A2	Boiling (atmospheric pres.)	215	206	27	30	145	5	15	66.0	63.7
B	Steaming	327	237	25	30	140	2	10	65.4	88.5
C1	Boiling under vacuum	192	189	20	45	125	2	15	91.2	87.2
C2	Boiling under vacuum	192	189	22	00	127	3	15	94.5	93.4
D	Boiling under vacuum	200	190	26	30	180	5	00	84.0	
E	Boiling under vacuum	192	186	26	50	150	4	30	100.1	
F	Boiling under vacuum	194	190	29	30	130	5	25	82.5	
G	Boiling under vacuum	200	192	25	45	142	3	45	95.7	

* From T. R. C. Wilson, Effect of creosote on strength of fir timbers, *Timberman*, Vol. 31, June 1930, p. 56.

† With respect to fiber stress at maximum load (modulus of rupture).

‡ Tests in series A1 to C2 conducted by U. S. Forest Service; remainder by other agencies.

Table 14. Strength Losses Resulting from Steaming of Unseasoned Shortleaf and Slash Pine Sapwood*

Steaming Conditions		Percentage Loss in Strength			
		Static Bending			Compression Parallel to Grain
Temperature, °F.	Hr.	Fiber Stress at Proportional Limit	Modulus of Rupture	Modulus of Elasticity	Maximum Crushing Strength
214	3	25.0	8.4	6.5	15.4
214	6	25.8	8.4	6.0	15.6
214	9	26.3	11.8	13.9	17.2
214	18	27.6	14.2	11.9	17.7
230	9	31.8	17.2	9.9	21.9
245	9	35.8	23.8	9.9	26.8
260	3	35.3	23.1	7.9	27.2
260	6	37.1	27.2	12.1	31.2
260	9	40.8	30.2	18.5	35.4
260	18	36.1	30.6	18.4	36.0

* Tests conducted on specimens maintained in a moist condition at 35°F. for several days or weeks prior to testing at room temperature.

From Stanley J. Buckman and Louis W. Rees, Effect of steaming on the strength of southern yellow pine, *Proc. Am. Wood Pres. Assn.*, Chicago, 1940, pp. 331–60.

white cedar poles and has been extended to cross ties of lodgepole pine, Engelmann spruce, and other species. Investigations on the strength of incised Douglas fir so treated yielded the following conclusions:[127]

1. Incising Douglas fir ties weakens them but little in compression perpendicular to the grain, the incised material showing an average strength that was more than 97 percent of that of the nonincised.

2. Incising Douglas fir beams affects the bending strength only slightly, the loss in fiber stress at proportional limit, modulus of rupture, and horizontal shear being slightly more than 2

---

[127] R. H. Rawson, The Effect on Douglas fir ties of incising and of creosoting by the boiling-under-vacuum process. *Proc. Am. Wood Pres. Assn.*, Chicago, 1926, pp. 191–6.

R. H. Rawson, A study of creosote treatment of six-inch by twelve-inch Douglas fir beams, covering boiling-under-vacuum-pressure process and the influence of incising, *Ibid.*, 1927, pp. 203–13.

percent. The combined effect of incising and treating may reduce the fiber stress at proportional limit slightly more than 10 percent, whereas in modulus of rupture and horizontal shear the reduction is less than 7 percent.

3. Seasoning Douglas fir by boiling under vacuum, using a maximum temperature of 192°F. under a minimum vacuum of 23 inches, does not weaken the timber to any further extent than does air seasoning in usual practice.

4. The slight loss due to incising is a great deal more than compensated for by the increased absorption and greater uniformity of penetration obtained. The incised timbers absorbed 43 percent more creosote than those not incised when treated under identical conditions.

Heartwood and Sapwood

In many species, examination of the end of a log reveals a relatively dark-colored inner core, the **heartwood,** surrounded by a lighter-colored zone, the **sapwood.** The sapwood is of vital importance in the life history of a living tree, being concerned with the conduction of soil moisture and contained mineral nutrients from the roots to the leaves, with the temporary storage of food, and with the mechanical support of the upper parts of the tree. Contrary to popular belief, the great majority of the cells composing the sapwood are dead; only those concerned with food storage (parenchyma cells) contain protoplasm and are actually alive. In the early life of a tree the woody portions are entirely composed of sapwood, but, as the trunk and larger branches increase in diameter by the formation of new sapwood layers on the outside of the already existing wood, the inner sapwood changes to heartwood. Such a change is accompanied by the death of the parenchyma cells and, in most species, by the deposition in the immediately adjacent wood of various substances, such as gums, tannins, resins, or oils. Heartwood derives its name entirely from its position in the tree; its sole function is that of mechanical support, and a tree may thrive even if its heartwood is completely decayed.

In some woods, such as black walnut, black locust, redwood, eastern red cedar, and the like, the character of the materials deposited in the heartwood is such as to produce a pronounced color contrast with the whitish sapwood. In other species, notably cottonwoods, aspens, spruces, and balsam, the contrast is so slight that it is difficult to distinguish the border line between the two portions. In some species the heartwood-sapwood division follows the annual growth rings, whereas in others, such as maple and hickory, it does not.

The proportion of sapwood to heartwood varies at different heights in a tree, being greater in the upper portions of a trunk than at the base. The percentage of sapwood also varies with the species, some woods forming heartwood much earlier in life than others. Narrow sapwood is characteristic of black locust, black ash, western larch, northern white cedar, and western red cedar, whereas in maple, white ash, hickory, and certain other woods the sapwood is so wide that it supplies most of the lumber cut from these species. Furthermore, within a given species the proportion of sapwood in a tree is largely dependent on the size and thriftiness of the crown. Accordingly, trees making rapid growth in the open usually develop a greater proportion of sapwood than the same kind of trees grown in dense stands, where competition with other trees for light, food, and growing space is keen. For this reason, "second-growth" hickory and other trees often attain considerable diameter before heartwood formation begins and usually possess a larger proportion of sapwood throughout their life than similar "virgin-growth" timber. However, in such woods as hickory, investigations have shown that even in very old virgin trees the thickness of the sapwood layer may be made to increase by thinning the stand, thus decreasing the competition with adjacent trees and increasing the rate of growth.[128]

Various and conflicting claims are sometimes made about the relative merits of heartwood and sapwood from the standpoint of strength. For many uses, the sapwood of such species as hickory and ash is popularly believed to be inherently superior, whereas in the case of structural timbers, such as oak and pine, the heartwood is often considered the better. The results of hundreds of thousands of tests conducted at the Forest Products Laboratory on various American woods have in general revealed no intrinsic difference in the strength of the two types of wood. However, exceptions to this general rule have been noted in redwood, western red cedar, and black locust, all containing large amounts of extractive in their heartwood. In these species the extractives formed in the wood as it changes from sapwood to heartwood have been found to increase the strength of the heartwood. Endwise compressive strength shows the greatest increase, modulus of rupture in bending somewhat less, and shock resistance the least. In fact, under some conditions the shock resistance of the heartwood appears to be lowered.[129]

---

[128] B. H. Paul, The relation of rate of growth to the production of white wood in hickory trees, *Southern Lumberman,* Nashville, Vol. 137, Oct. 1, 1929, p. 67.

When actual differences in strength between heartwood and sapwood do occur, they are usually associated with variations in density and prevalence of defects. As has been previously explained, the conditions under which a tree grows have a marked effect on the density and resultant strength of its wood. If the growing conditions are such as to maintain the production of wood of high density throughout the life of a tree, the heartwood and sapwood should not exhibit any pronounced difference in clear-wood strength. On the other hand, if the density of the wood produced with the passage of time decreases or increases, the clear-wood strength of the sapwood will correspondingly decrease or increase.[130] Although exceptions frequently occur, it may be said that, as a general rule, the sapwood laid on late in the life of a mature tree is softer, lighter, weaker, and more even-textured than the wood produced during the earlier stages of the tree's development and subsequently transformed to heartwood.

From the point of view of freedom from defects, the sapwood is normally decidedly superior. The lower branches which prevail almost to the ground in young trees eventually die and are broken off. Subsequent diameter growth of the trunk may completely cover the stubs, but they remain as knots in the interior portions of the tree. In consequence, the sapwood of the more sizable trees, and particularly of those grown in dense stands where crowding brings about the loss of the lower branches relatively early in life, will contain fewer knots than the heartwood. Furthermore, the heartwood of a living tree is more subject to shake, insect attack, and decay,[131] any of which may materially reduce the strength of the wood. It is evident, therefore, that the strength of a given piece of wood is not dependent on whether it is heartwood or sapwood, but rather on the actual quality of the piece, as determined by its density and the extent to which defects are present.

---

[129] R. F. Luxford, Effect of extractives on the strength of wood, *Jour. Agr. Res.*, Washington, Vol. 42, 1931, pp. 801–26.

[130] The relations between the density and strength of wood in conifers and ring-porous and diffuse-porous hardwoods are discussed on pages 152–66.

Since structural timbers and wood in other forms are frequently used in exposed situations, the resistance that such material offers to deterioration by decay is often an important consideration. Consequently, under such conditions, it is common practice to specify the use of either naturally durable wood or that made artificially decay-resistant by treatment with creosote or other suitable preservative. From the standpoint of prolonged resistance to decay, a satisfactory preservative treatment is to be preferred, particularly as it is adaptable to practically all kinds of wood.

In natural durability, heartwood is, in general, decidedly superior to sapwood, although, as has been explained under the discussion of Decay, not all heartwood is resistant to decay (see pages 109–15). On the other hand, when the material is to be impregnated with preservatives, a large amount of sapwood is preferable, since with few exceptions it is more readily penetrated than heartwood. However, there is a wide range in the ease with which the various woods may be treated. Some, such as the heartwood of white oak and red gum, are very difficult to impregnate; others, as the heartwood of Douglas fir, southern pine, western larch, and the spruces, are somewhat less refractory; whereas still others, including red oak, sap pine, sap gum, and the heartwood of ponderosa pine, are treated with ease. In eastern hemlock, both heartwood and sapwood are about equally resistant to impregnation.[132]

[131] This is in distinct contrast to the condition existing in wood in service, in which the heartwood is normally more durable, and may be accounted for by the fact that in the living tree the moisture content of the sapwood is so high as to reduce the available air supply below the minimum necessary for the development of decay.

[132] C. H. Teesdale, *Relative resistance of various conifers to injection with creosote,* U. S. Dept. Agr. Bul. 101, Washington, 1914.

Also C. H. Teesdale and J. D. MacLean, *Relative resistance of various hardwoods to injection with creosote,* U. S. Dept. Agr. Bul. 606, Washington, 1918.

J. D. MacLean, *Manual on preservative treatment of wood by pressure,* U. S. Dept. Agr. Misc. Publ. 224, Washington, 1935, pp. 16–17.

In addition to color, prevalence of defects, durability, and treatability, there are a number of other characteristic general differences between heartwood and sapwood. Sapwood seasons more rapidly than heartwood and is usually less subject to seasoning defects. However, it tends to shrink and swell more with changes in atmospheric humidity. The reduced shrinkage of heartwood is of particular significance in colored woods, such as redwood, that contain substantial amounts of extractive materials in the cell walls and is attributed to the "bulking" effect of these substances. The greater permeability of the sapwood is a disadvantage in woods used for tanks, wood pipe, tight cooperage, and other purposes that involve the confinement of liquids. The relative lack of odor and leachable coloring materials in the sapwood may be an advantage in certain uses, but a disadvantage in others.

Live Versus Dead Timber

Specifications for the purchase of timber sometimes stipulate that material from trees that have been killed by fire or other causes will not be accepted, regardless of how sound the wood may be. That such a prejudice is unfounded is borne out by the available information, which indicates that timber cut from insect- or fire-killed trees or from chestnut trees killed by the chestnut blight is as suitable for structural uses as that from live trees of similar quality, provided the wood has not been subsequently injured by decay or by further insect attack.[133] If the trees are left standing on the stump too long after being killed, they may be seriously deteriorated by decay or insect attack or badly checked as the wood dries out. However, deterioration that is just as serious may take place in timber from live trees if it is not properly cared for after being cut. It should be borne in mind that the great bulk of the wood in a living tree is dead, only a comparatively small proportion of the sapwood cells containing living protoplasm.

---

[133] *Comparative value of timber cut from live and dead trees*, For. Prod. Lab. Tech. Note 101, Madison.

A utilization guide for blight-killed chestnut, For. Prod. Lab. Tech. Note 224, Madison.

T. A. McElhanney and R. S. Perry, Report on tests of the relative strength of green-cut and fire-killed western cedar pole timber, *Western Lumberman,* Vancouver, B. C., Vol. 25, Sept. 1928, pp. 886, 896–7.

Season of Cutting[134]

The theory is frequently advanced that the season of the year in which timber is cut has a marked influence on certain properties of wood. To the material felled during the winter months are often ascribed certain inherent advantages over that cut at the other seasons of the year—greater durability, less liability to checking during seasoning, better color, and even increased strength. However, this reputed inherent superiority of winter-cut timber has not been borne out in the various investigations that have been made, although it is recognized that the climatic differences during the several seasons may have some effect on the wood, particularly in regard to deterioration during seasoning.

The explanation most frequently offered for the presumed superiority of winter-cut material is that the sap[135] is drawn down out of the crown and trunk of a tree during the late fall months and taken back up again in the spring; hence, it is claimed, the wood cut in the winter is drier than that felled during the rest of the year. In support of the contention that "sap goes up" in a tree in the spring of the year, the fact is cited that in certain trees, such as the sugar maple, the sap "bleeds" or flows more freely from wounds made in the early spring than at other times. This presumed winter decrease in moisture in the tree trunk has not been substantiated by experiment, however, such tests as have been carried out showing that there is as much, if not more, moisture in a tree during the winter as in the summer months.[136] The more profuse "bleeding" of certain trees during the early spring is presumably due to (1) the rather rapid daily changes in temperature which occur at this time of year and cause a contraction and expansion of the outer sapwood layers, and (2) the continued activities of those roots that are below the frost line. During winter months the intake of moisture from the lower roots is not offset by the evaporation of water from the crown of the tree, particularly in those species that lose their leaves during the dormant period. Consequently there is a gradual building up of pressure within the tree that is not relieved until the buds open and evaporation begins in the newly forming leaves.

---

[134] For more detailed discussion of this subject see S. J. Record, Sap in relation to the properties of wood, *Proc. Am. Wood Pres. Assn.*, Chicago, 1913, pp. 160–6.

[135] The term "sap" is popularly applied to the moisture in unseasoned wood. This is not pure water but contains small quantities of dissolved mineral nutrients and organic matter.

[136] Maximum moisture content in deciduous hardwoods appears to occur immediately prior to leaf opening in the spring, and minimum moisture just before leaf fall in the autumn. No important seasonal variations are apparent in softwoods. See R. Darnley Gibbs, Studies of wood II, On the water content of certain Canadian trees and on changes in the water—gas system during seasoning and flotation, *Canadian Jour. Res.*, Vol. 12, 1935, pp. 727–60.

The reputed greater durability of winter-cut wood is also based on the seasonal variation in the composition of the sap, the claim sometimes being made that in the summer especially the sap contains certain chemical substances that affect the properties of wood and make it particularly susceptible to decay. Although seasonal differences in sap composition undoubtedly do occur, particularly in starch and sugar content, they are confined to the sapwood, which is invariably lacking in natural durability. Any prolongation of life, due to this cause, would be slight at best.

The superiority of winter-felled timber, where such exists, is actually dependent on the climatic conditions and the care with which the material is handled after felling. During cold weather the drying of the wood proceeds slowly and much less checking and splitting of the wood is likely to occur than during the warm summer months. Furthermore, decay is inhibited by the low temperatures prevailing in most sections of the country during the winter, and the exposed portions of the wood have a chance to season below the minimum moisture content necessary for the development of decay before the wood-destroying fungi become active. Likewise, the various wood-boring insects that attack unseasoned timber are held in check during the cold months. However, these advantages of winter-cut wood may be completely nullified if the timber felled at other seasons of the year is carefully handled.

In conclusion it may be said that, if trees felled at various times during the year are cut into lumber immediately after felling and kiln-dried in exactly the same manner, no difference due to the season of cutting will be noted.

Duration of Stress

The relationship between magnitude of load and logarithm of time over which the load is supported is shown in Fig. 51. The effect of long-continued loading is discussed in connection with working stresses on pages 210–11. Loads greater than those carried under standard static testing conditions can be supported when stress is of only a few seconds' duration. Recent work at the Forest Products Laboratory, using special equipment for the rapid loading of test specimens, has shown that the load supported by beams and columns for short periods is a function of both loading time and duration of stress.[137] In this latter work **duration of stress** is considered as the time interval following the completion of its application during which a constant load is maintained.

On the basis of these results, it is estimated that a Sitka spruce beam loaded in 0.2 second to 109 percent of its standard static-bending maximum load would fail after 2.8 seconds duration of stress, whereas a similar beam loaded at a uniform rate over a loading period of 3 seconds would support a load 117 percent of that attained under standard static-bending conditions (see Fig. 51).

In the same tests variation in rate of loading failed to influence modulus of elasticity, but a noticeable *relaxation*, or reduction in stress, was shown when the deflection of rapidly loaded beams was maintained. Ten minutes after attaining a rapidly developed maximum stress (equivalent to modulus of rupture in standard static tests of similar specimens), Sitka spruce beams maintained at constant deflection retained a residual stress 85 percent of maximum. This represents a 15 percent reduction in load. At lower loads relaxation was less apparent and probably would not be appreciable at loads less than 50 percent of the maximum carried under standard static test conditions. The influence of such short periods of stress is especially important from the standpoint of aircraft and similar uses in which design is based on stresses of but a few seconds duration.

---

[137] M. P. Brokaw and G. W. Foster, *Effect of rapid loading and duration of stress on the strength properties of wood tested in compression and flexure,* For. Prod. Lab. Rept. 1518, Madison, 1945.

Fatigue

Fatigue refers to the effect of numerous cycles of repeated stress on a material. Repetition for a few times of stresses below ultimate strength probably has no appreciable effect on modulus of rupture or maximum crushing strength, although modulus of elasticity is reduced after the first loading. In tests conducted at the Forest Products Laboratory, Kommers found that after ten repetitions of loading in the same direction to within a few percent of ultimate strength, Sitka spruce and Douglas fir specimens loaded in static bending and compression parallel to the grain were practically as strong as the control specimens.[138] Modulus of elasticity, however, was reduced by as much as 20 percent. A tendency for this reduction to continue at a progressively slower rate with increased number of repetitions was indicated.

Relatively few studies have been made of the fatigue characteristics of wood, but available data indicate that the **endurance limit,** the maximum stress that can be imposed an infinite number of times without failure, of beams subjected to reversed loading, in which the fibers are alternately stressed in tension and compression, is 25 to 30 percent of modulus of rupture.[139] Recent tests at the Forest Products Laboratory[140] have, in general, confirmed the results of earlier studies. In tests of yellow birch, yellow poplar, Sitka spruce, and Douglas fir, endurance strength for each species at 50 million cycles of reversed stress was approximately 27 percent of modulus of rupture. When loading was repeated in one direction only, endurance strength at 50 million cycles was approximately 36 percent of modulus of rupture.

REFERENCES

American Society for Testing Materials: Definitions of terms relating to timber. Serial Designation D9-30, 1930 *Book of Standards*. Am. Soc. Test. Mat., Philadelphia, Pt. II.

---

[138] W. J. Kommers, *Effect of ten repetitions of stress on the bending and compressive strengths of Sitka spruce and Douglas fir*, For. Prod. Lab. Rept. 1320, Madison, 1943.

[139] Markwardt and Wilson, footnote 94, pp. 59–61.

[140] W. J. Kommers, *The fatigue behavior of wood and plywood subjected to repeated and reversed bending stresses*, For. Prod. Lab. Rept. 1327, Madison, 1943.

Betts, Harold S.: *Timber—its strength, seasoning, and grading.* McGraw-Hill Book Co., New York, 1919.

Boyce, J. S.: *Decays and discolorations in airplane woods.* U. S. Dept. Agr. Bul. 1128, Washington, 1923.

Cline, McGarvey and A. L. Heim: *Tests of structural timbers.* U. S. Dept. Agr. For. Serv. Bul. 108, Washington, 1912.

Desch, H. E.: *Timber: its structure and properties.* Macmillan and Co., London, 1947.

Forest Products Laboratory: *Wood handbook,* rev. U. S. Dept. Agr. Unnumbered Publ., Washington, 1940.

———: *Manual for the inspection of aircraft wood and glue for the United States Navy.* U. S. Navy Dept. Bur. Aero., Washington, 1941.

———: *Wood aircraft inspection and fabrication.* ANC Bul. 19, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1943.

———: *Wood inspection.* Air Tech. Service Command Tech. Directive A320-2, Wright Field, 1944.

Forsaith, C. C.: *The technology of New York State timbers.* N. Y. State Coll. For., Tech. Publ. 18, Syracuse, 1926.

Holtman, Dudley F.: *Wood construction—principles, practice, details.* McGraw-Hill Book Co., New York, 1929.

Koehler, Arthur: *The properties and uses of wood.* McGraw-Hill Book Co., New York, 1924.

———: *Causes of brashness in wood.* U. S. Dept. Agr. Tech. Bul. 342, Washington, 1933.

Kollmann, Franz: *Technologie des Holzes.* Julius Springer, Berlin, 1936.

McElhanney, T. A., and associates: *Canadian woods: Their properties and uses.* Canada Dept. Int., Ottawa, 1935.

Markwardt, L. J.: Wood as an engineering material. *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 43, 1943, pp. 435–92.

——— and T. R. C. Wilson: *Strength and related properties of woods grown in the United States.* U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935.

Newlin, J. A., and R. P. A. Johnson: *Basic grading rules and working stresses for structural timbers.* U. S. Dept. Agr. Dept. Circ. 295, Washington, 1923.

——— and ———: Structural timbers—defects and their influence on strength. *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 24, Pt. 2, 1924, pp. 975–87.

Paul, Benson H.: *The application of silviculture in controlling the specific gravity of wood.* U. S. Dept. Agr. Tech. Bul. 168, Washington, 1930.

Record, Samuel J.: *The mechanical properties of wood.* John Wiley & Sons, New York, 1914.

Tiemann, Harry Donald: *Wood technology.* Pitman Publ. Corp., New York, 1942.

Wilson, T. R. C.: *Strength-moisture relations for wood.* U. S. Dept. Agr. Tech. Bul. 282, Washington, 1932.

PART 3

Working Stresses For Structural Lumber

INTRODUCTION

For convenience in designing structural timbers, strength values derived from laboratory-test data are commonly adjusted to meet the conditions that may be imposed on the material in actual service. To be efficient, these adjusted values, or **working stresses** as they are known, should provide for the closest possible utilization of wood commensurate with absolute assurance of satisfactory service and safety. Working stresses are commonly derived for *fiber stress in bending* (bending strength), *horizontal shear, compression parallel to grain* (strength as a column), and *compression perpendicular to grain* for the more important structural woods. In addition, values are set up for *modulus of elasticity* (stiffness), although these are actual average test values and not adjusted working stresses.

In the past, tables of working stresses for wood, found in various engineers' handbooks and in the building codes of many cities, for the most part were far from agreement on the values assigned to any given species. Further, such tables almost without exception placed no limitation on the grade or quality of the material for which the assigned values were intended.[1]

In an attempt to correct this lack of standardization and to insure safe and efficient utilization of wood in construction, the Forest Products Laboratory, a branch of the United States Forest Service, recommended in 1934 a uniform basis for the establishment of working stresses for grades conforming to the provisions of American Lumber Standards.[2] Uniform stress grading of structural lumber, based on these principles, has been adopted by the lumber industry, and, although unfortunately not yet incorporated in all building codes, standardized working stresses for all established *stress grades* of lumber are now available to the designer.

---

[1] *Recommended building code requirements for working stresses in building materials,* U. S. Dept. Comm. Bldg. Code Com. Rept., Washington, 1926.

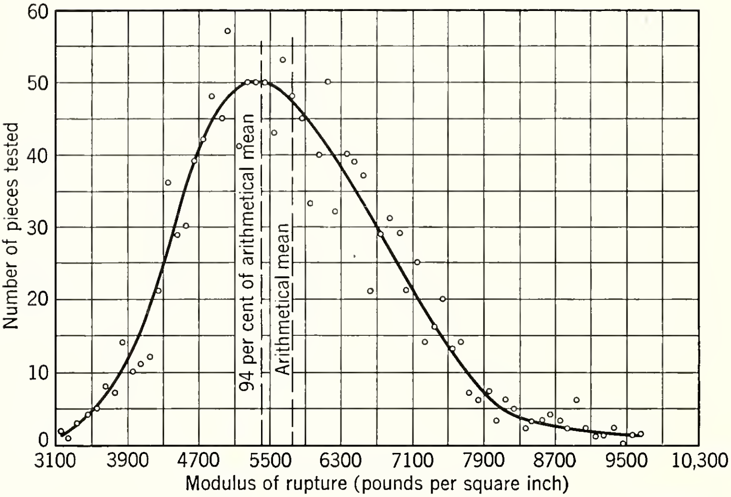
[2] These basic provisions, as published in revised form by the U. S. Department of Commerce in *Lumber,* Simplified Practice Recommendation R16-39, are incorporated in a later section.

Although working stresses are intended for direct application to lumber of the grades and dimensions commonly employed in the construction of buildings, bridges, and similar structures, many of the principles involved in their derivation are applicable to numerous other uses in which wood is subjected to stress.

FACTORS CONCERNED IN THE DERIVATION OF BASIC STRESSES

Working stresses are not derived directly from laboratory-test values but rather are based on the determination of intermediate **basic-stress** values for defect-free wood. Values for basic stress are, in effect, working stresses for clear, straight-grained lumber. They have been derived from average values for the fundamental strength properties of each kind of wood, as determined from hundreds of thousands of tests conducted at the Forest Products Laboratory, and modified according to the characteristics of the various species concerned, as revealed by the performance of structural timbers. In the derivation of basic-stress values, consideration has been given to (1) variability in the strength of the clear wood, (2) duration of load, and (3) the possibility of accidental overload. Only the reduction introduced to take care of accidental overloading is a true "factor of safety."

Although the strength of clear wood, particularly in compression and bending, may be increased to a marked degree by seasoning, basic-stress values are founded on the strength properties of unseasoned wood. Structural timbers are commonly placed in service in an unseasoned, or only partially seasoned, condition. Even if such material is thoroughly seasoned prior to installation, loss of moisture in timbers of structural size is normally accompanied by checking and other drying defects, which tend to offset the gain in strength due to lowered moisture content. Tests have indicated that the lower grades of large timbers and about 25 percent of the higher grades do not increase in strength on drying, although the average strength of the material of better quality is raised slightly. The derivation of basic stresses from tests of green or unseasoned wood may thus be seen to represent a more or less conservative practice, dependent largely on the extent to which defects may develop during seasoning of the timber.



Copy Prepared by Forest Products Laboratory

Fig. 50. Variability in modulus of rupture of unseasoned Sitka spruce. All specimens were clear, but in selecting them no attention was paid to specific gravity or position in the tree.

Variation in Strength of Clear Wood

Since basic stresses for any kind of timber are derived from average strength values, as determined from laboratory tests on small specimens, they must take into account the possible variation in strength below that average. In other words, consideration must be given not to the material of average strength, but to the weakest piece that may be used. This is of vital importance, as it is not unusual to find test specimens having only about one-half to three-fourths the average values for the species in some strength properties. The probable variation in the strength of unseasoned clear wood is indicated in the accompanying frequency curve for modulus of rupture of Sitka spruce (Fig. 50), which is also representative of the normal variation of most other woods. Several observations are to be made from this variability curve: (1) The greater number of tests (711 out of 1373) give values below the arithmetical mean, but the greater range of variation is above this average; (2) the most probable value (highest point in curve) is about 94 percent of the arithmetical mean, whereas (3) another 25 percent are more than 12 percent above it; and (4) approximately 8 percent of the values are more than 25 percent below the average.[3,4] These differences in strength are usually associated with variations in density, which may in turn be accounted for by differences in the character of growth or other factors.

Inasmuch as the relative density of any two pieces of the same species will afford an index to their comparative strength (see discussion of Density, pages 152–8), it is evident that density specifications are of considerable value in the selection of material for structural purposes. However, such specifications are of necessity confined to southern pine and Douglas fir, since there is at present no ready and accurate method of determining density in the other kinds of common structural timbers. Nevertheless, in any species, it is possible to guard against the use of the very weak pieces, the clear-wood strength of which is less than 75 percent of the average, by excluding all exceptionally lightweight material. Such a rejection is specified in the basic provisions for grading rules conforming to American Lumber Standards, which stipulate that "no pieces of exceptionally light weight shall be permitted in any grade." Provision must still be made, however, for the acceptable pieces that may have only about three fourths of the average strength and, in deriving basic stresses, the strength of clear wood is considered as being only 75 percent of the average test values for most properties.

---

[3] *Recommended building code requirements for working stresses in building materials,* footnote 1, p. 44.

Also J. A. Newlin, Unit stresses in timber, *Proc. Am. Soc. Civil Eng.,* New York, Vol. 52, Sept. 1926, p. 1437. Also in *Trans. Am. Soc. Civil Eng.,* New York, Vol. 91, Dec. 1927, p. 401.

[4] For detailed discussion of the range of variability in the specific gravity of wood and its significance see L. J. Markwardt, *Comparative strength properties of woods grown in the United States.* U. S. Dept. Agr. Tech. Bul. 158, Washington, 1930, pp. 34–7. Also L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935, pp. 17–21.

In *close-grained* Douglas fir and redwood it is possible to eliminate certain material of low strength by applying the so-called ring count or *rate-of-growth rule,* which provides for material having a rate of growth that is usually associated with relatively high density in these species. The derived basic stresses in compression and in fiber stress in bending for close-grained Douglas fir and redwood are increased $1/15$ because of this requirement.

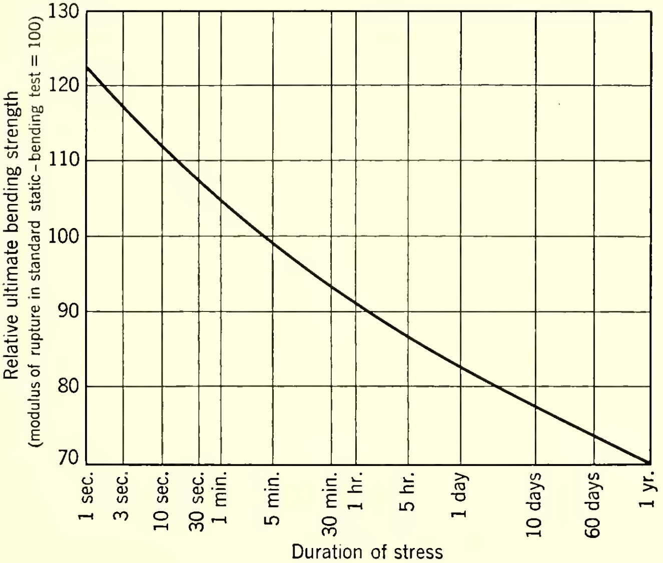
Southern pine and Douglas fir are both characterized by a distinct contrast between the two portions of the annual ring, and the approximate density of a piece may be readily determined from an estimate of the average proportion of summerwood. Consequently, by applying a suitable *density rule* to these two woods, it is possible to secure material of high character from the standpoint of strength, and uniformity of strength, of the clear wood. This is done in grading rules conforming to American Lumber Standards and, as a result, improved properties for dense material are recognized in the basic stresses for these two woods. Basic stresses in compression, fiber stress in bending, and shear for dense southern pine and Douglas fir are one sixth greater than the values assigned to material not selected according to the density rule.

Duration of Load

Duration of stress has an important bearing on the load that a given timber will support. Tests have demonstrated that the load required to break beams in long-time loading is about two thirds of that required to break them under ordinary static loading in the laboratory. When the duration of stress is shortened still further, as in impact loading, the load required to break a timber is increased over that observed in static-bending tests.

The relation between ultimate bending strength and duration of load is illustrated for Sitka spruce in the accompanying diagram (Fig. 51). In the curve the value derived from the standard static-bending test, which requires on the average about 5 minutes, is taken as 100 percent. Few data are available for periods of time much less than 1 second. A logarithmic scale is used for the time coordinate.

The values for basic stress are for the most critical duration of stress, namely *long-time loading,* and are so reduced as to insure that stress will be kept within the proportional limit. In deriving these values for the several strength properties, consideration is given to the fact that the effect of increased duration of stress on strength is directly related to the difference between proportional limit and ultimate strength. This difference, however, is not necessarily the same for structural timbers as for small clear specimens.[5] Whereas formerly less reduction was made in laboratory-test values in providing for the effect of long-time loading in compression parallel to grain than in fiber stress in bending since the proportional limit was supposedly closer to ultimate strength in the former property, recent duration of load tests at the Forest Products Laboratory indicate that the long-time load limit for structural timber is approximately two thirds of the ultimate load in static testing in both properties.



Forest Products Laboratory Data

FIG. 51. Variation in ultimate bending strength with duration of stress. Duration of stress is defined here as the total time between application of initial load and attainment of ultimate load or failure.

---

[5] *Recommendations for basic stresses,* For. Prod. Lab. Rept. R1715, Supplement 2 to U. S. Dept. Agr. Misc. Publ. 185, Madison, 1948.

Accidental Overloading

Although the loads to which a structure is subjected should not intentionally exceed the design load, some provision must nevertheless be made for small accidental overloads. In deriving basic stresses for clear wood a reduction of two fifths in the value for fiber stress in bending has been provided for accidental overloading, and in compression parallel to grain the corresponding reduction amounts to about one third. No specific reduction for overloading is provided in compression perpendicular to grain or in shear, although this factor is undoubtedly included in the large over-all reduction provided in the case of shearing stress.

BASIC-STRESS VALUES FOR CLEAR WOOD

Basic stresses for clear material of 38 different species or categories of lumber are shown in Table 15. The values shown in the table represent an increase in certain types of stress over those used prior to World War II but are not so high as those stipulated in Governmental wartime conservation regulations and subsequently recommended as standard practice by the lumber manufacturers' associations.[6] With some modification to be discussed later, current working-stress recommendations of the National Lumber Manufacturers Association conform to these basic-stress values.[7]

The effect of the several factors that influence the determination of basic stresses is by no means the same for all strength properties. In the following paragraphs the relation of these components to the total reduction factor, used in deriving basic stresses from laboratory-test values, is briefly considered for each of the properties listed in Table 15, namely: extreme fiber stress in bending, compression perpendicular to grain, compression parallel to grain, horizontal shear, and modulus of elasticity. It should be borne in mind throughout the ensuing discussion, however, that the recommended basic stresses are quite closely related to

[6] *National emergency specifications for the design, fabrication, and erection of stress-grade lumber and its fastenings for buildings,* War Prod. Board, Cons. Division, Directive No. 29, Washington, Aug. 9, 1943. Also *National design specification for stress-grade lumber and its fastenings,* Nat. Lbr. Mfrs. Assn., Washington, 1944.

[7] *National design specification for stress-grade lumber and its fastenings,* rev., Nat. Lbr. Mfrs. Assn., Washington, 1948.

TABLE 15. BASIC STRESSES FOR CLEAR WOOD UNDER LONG-TIME LOADING*

Species	Extreme Fiber in Bending or Tension Parallel to Grain, psi	Maximum Horizontal Shear, psi	Compression Perpendicular to Grain, psi	Compression Parallel to Grain, psi	Modulus of Elasticity in Bending, 1000 psi
Ash, black	1450	130	300	850	1100
Ash, commercial white	2050	185	500	1450	1500
Beech	2200	185	500	1600	1600
Birch, sweet and yellow	2200	185	500	1600	1600
Cedar, Alaska	1600	130	250	1050	1200
Cedar, northern white and southern white	1100	100	180	750	800
Cedar, Port Orford	1600	130	250	1200	1500
Cedar, western red	1300	120	200	950	1000
Cottonwood, eastern	1100	90	150	800	1000
Cypress, southern	1900	150	300	1450	1200
Douglas fir, coast region	2200	130	320	1450	1600
Douglas fir, coast region, close-grained	2350	130	340	1550	1600
Douglas fir, Rocky Mt. region	1600	120	280	1050	1200
Douglas fir, dense, all regions	2550	150	380	1700	1600
Elm, American and slippery	1600	150	250	1050	1200
Elm, rock	2200	185	500	1600	1300
Fir, California red, grand, noble and white	1600	100	300	950	1100
Fir, balsam	1300	100	150	950	1000
Gum, black and red	1600	150	300	1050	1200
Hemlock, eastern	1600	100	300	950	1100

TABLE 15. BASIC STRESSES FOR CLEAR WOOD UNDER LONG-TIME LOADING*—*Continued*

Species	Extreme Fiber in Bending or Tension Parallel to Grain, psi	Maximum Horizontal Shear, psi	Compression Perpendicular to Grain, psi	Compression Parallel to Grain, psi	Modulus of Elasticity in Bending, 1000 psi
Hemlock, western	1900	110	300	1200	1400
Hickory, true and pecan	2800	205	600	2000	1800
Larch, western	2200	130	320	1450	1500
Maple, sugar and black	2200	185	500	1600	1600
Oak, commercial red and white	2050	185	500	1350	1500
Pine, western white, eastern white, ponderosa and sugar	1300	120	250	1000	1000
Pine, jack	1600	120	220	1050	1100
Pine, lodgepole	1300	90	220	950	1000
Pine, red (Norway)	1600	120	220	1050	1200
Pine, southern yellow	2200	160	320	1450	1600
Pine, southern yellow, dense	2550	190	380	1700	1600
Poplar, yellow	1300	120	220	950	1100
Redwood	1750	100	250	1350	1200
Redwood, close-grained	1900	100	270	1450	1200
Spruce, Engelmann	1100	100	180	800	800
Spruce, red, white, and Sitka	1600	120	250	1050	1200
Tamarack	1750	140	300	1350	1300
Tupelo	1600	150	300	1050	1200

---

* From *Recommendations for basic stresses*, For. Prod. Lab. Rept. R1715, Supplement 2 to U. S. Dept. Agr. Misc. Publ. 185, 1948.

experience and judgment in the use of timber for many years; consequently, the reduction factor by which the basic stress may be calculated from laboratory-test values is often considerably modified on the basis of this experience and judgment. Insofar as possible, the systematic procedure for the establishment of basic-stress values is shown by typical examples.

Extreme Fiber Stress in Bending

Basic-stress values for extreme fiber in bending are derived from average values for modulus of rupture as obtained from laboratory tests in static bending on small clear unseasoned specimens.[8] These test values are adjusted in consideration of the three factors previously discussed: variation in the strength of clear wood, long-time loading, and accidental overloading. The values for individual species presented in Table 15 have not been determined strictly by the systematic application of a precise formula but have been established with additional consideration of the structural performance record of the particular species.

In general, however, the over-all reduction includes a lowering of the laboratory-test value for modulus of rupture by one fourth for variability, one third for long-time loading, and two fifths for accidental overloading. In deriving the basic stress for coast Douglas fir, for example, the average modulus of rupture for small, clear, unseasoned specimens tested in static bending (7600 pounds per square inch) is reduced as follows:

$$7600 \times 3/4 \times 2/3 \times 3/5 = 2280 \text{ pounds per square inch}$$

As indicated in Table 15, this value has been adjusted to 2200 pounds per square inch, on the basis of structural experience with this species.

---

[8] "Both proportional limit (fiber stress at proportional limit) and ultimate strength (modulus of rupture) have been considered, but the latter is taken as the more dependable basis for the determination of basic stress. The following specific reasons are given for this choice: (1) There is a personal element in determining the proportional limit, (2) slight inaccuracies in measurements of deflections often cause considerable error in proportional limit values, (3) defects in structural timbers may be such that, in testing, certain portions are stressed to or beyond the proportional limit without discovery, and (4) there is an element of safety in the differential of strength between the proportional limit and modulus of rupture values."—J. A. Newlin and T. R. C. Wilson, *Mechanical Properties of woods grown in the United States,* U. S. Dept. Agr. Bul. 556, Washington, 1917, p. 13.

Since certain coast-type Douglas fir and redwood grades include a provision for close-grained wood, eliminating some of the weakest rapid-growth material, basic-stress values for such material have been increased by $\frac{1}{15}$. Thus, close-grained coast Douglas fir has a basic-stress value for extreme fiber in bending of 2350 pounds per square inch. In recognition of the still greater strength provided when selection for density is specified, values for dense southern yellow pine and Douglas fir (coast and Rocky Mountain types) are increased by $\frac{1}{6}$, and, for both of these important structural timbers, a basic stress value of 2550 pounds per square inch ($2200 \times 1\frac{1}{6}$) has been established.

In general, the weakest acceptable specimen of clear wood, selected only by the exclusion of exceptionally lightweight material, will have an actual factor of safety, or provision for accidental overload, of approximately $1\frac{2}{3}$; the average specimen a factor of safety for long-time loading of about $2\frac{1}{4}$, and for a few minutes (if a 5-minute duration of stress is assumed, as in static bending), a factor of safety of approximately $3\frac{1}{3}$. These basic-stress values for extreme fiber in bending (Table 15) represent a 10 percent increase over those formerly recommended by the Forest Products Laboratory.

Compression Perpendicular to the Grain

Basic stresses in compression perpendicular to the grain are derived from average laboratory-test values for fiber stress at proportional limit, which are indicative of the greatest stress that can be applied without injury to the wood. It is practically impossible to determine maximum strength in this respect, either in test or in service. Reduction factors ranging from about $1\frac{1}{3}$ to 2 have been applied to laboratory values for stress at proportional limit in the establishment of the basic-stress values shown in Table 15. Coast Douglas fir, for example, with a laboratory-determined fiber-stress value of 510 pounds per square inch in the unseasoned condition, has an assigned basic-stress value of 320 pounds per square inch, involving a total reduction factor of about $1\frac{3}{5}$. This reduction allows chiefly for possible variation in the strength of clear wood. The neglect of other factors is justified on the basis of the rather inconsequential effect of overloading in compression perpendicular to the grain.

Basic-stress values for close-grained Douglas fir and redwood, and dense southern yellow pine and Douglas fir are increased by $\frac{1}{15}$ and $\frac{1}{6}$, respectively, as a result of the improved strength of such selected material. A value of 340 pounds per square inch ($320 \times 1\frac{1}{15}$) has been designated for close-grained Douglas fir, and 380 pounds per square inch ($320 \times 1\frac{1}{6}$) for dense southern yellow pine and Douglas fir.

The computed basic stress values are adjusted on the basis of the characteristics shown by individual species as indicated by the over-all reduction factors of 1.36 for Sitka spruce and 2.08 for redwood.

Recent studies at the Forest Products Laboratory indicate no basis for increasing these long-established basic-stress values when wood is used in the green condition. However, increases of 10 percent in these basic-stress values for material that is surface-dry when placed in service and of 20 percent for seasoned material used under continuously dry conditions are recommended.[9]

Compression Parallel to the Grain

Basic stresses in compression parallel to the grain are also determined more in the light of experience and judgment than by precise formula. A total reduction factor of approximately $2\frac{3}{4}$, however, applies to a considerable number of the species listed in Table 15 and may be considered to provide a reduction of about $\frac{1}{5}$ for variability, $\frac{1}{3}$ for long-time loading, and $\frac{1}{3}$ for accidental overloading. In deriving the basic stress in compression parallel to the grain for coast Douglas fir, the average laboratory value for maximum crushing strength in the unseasoned condition may be considered to be reduced approximately as follows:

$$3890 \times \frac{4}{5} \times \frac{2}{3} \times \frac{2}{3} = 1380 \text{ pounds per square inch}$$

The established basic stress for coast Douglas fir, as shown in the table, is actually 1450 pounds per square inch. As noted previously, basic-stress values for close-grained redwood and Douglas fir are increased by $\frac{1}{15}$, and for dense Douglas fir and southern yellow pine by $1/6$. In Table 15 the basic stress in compression parallel to the grain for close-grained Douglas fir is shown as 1550 pounds per square inch ($1450 \times 1\frac{1}{15}$), and for dense Douglas fir as 1700 pounds per square inch ($1450 \times 1\frac{1}{6}$).

---

[9] *Recommendations for basic stresses,* footnote 5.

The basic stresses shown for compression parallel to grain represent no change as a result of a recent re-examination of available data at the Forest Products Laboratory.

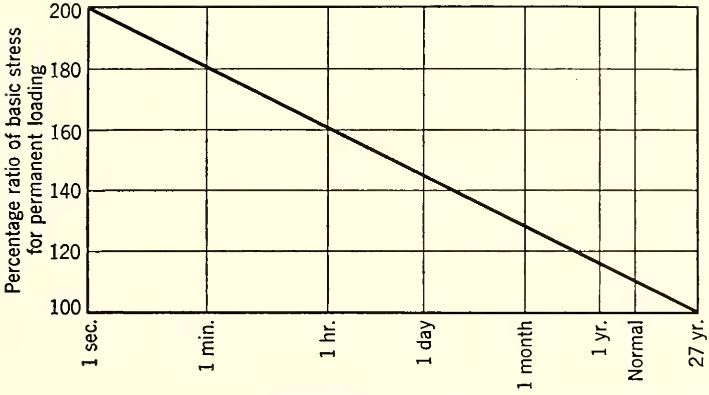
Maximum Horizontal Shear

Basic stresses for maximum horizontal shear in beams, stringers, joists, and planks are derived from values for shearing strength parallel to the grain, as determined in tests of small clear specimens in the unseasoned condition. A relatively high reduction factor, approximately 6 to 8, is used in adjusting test values to the basic-stress values given in Table 15. A major part of this reduction is introduced as a stress-concentration factor. Horizontal-shear values for Douglas fir, for example, involve an over-all reduction of 930/130 or approximately 7. No increase is allowed for close-grained wood in redwood and Douglas fir where such material is segregated by grade, although the usual increase of $1/6$ is applied for dense Douglas fir and southern yellow pine. A basic stress value of 150 pounds per square inch ($130 \times 1\frac{1}{6}$) has been established for dense Douglas fir on this basis.

The large reduction factor involved in the establishment of basic values for horizontal shear is necessitated by the empirical nature of the block-shear test used in the determination of laboratory shear values. When beams fail in horizontal shear, the calculated shearing stresses are invariably less than the values indicated by the standard laboratory block-shear test. Thus, in the establishment of basic-stress values, the comparative values determined in laboratory testing of small blocks have been considerably modified on the basis of experience gained in the testing of timbers of structural size. Values shown for horizontal shear include a 10 percent increase over those formerly recommended by the Forest Products Laboratory.

Modulus of Elasticity

Values for modulus of elasticity given in Table 15 are not reduced values comparable to other basic-stress values. They are merely the average modulus of elasticity values determined in static-bending tests of small clear unseasoned specimens. For design purposes, modulus of elasticity values have been rounded off to the nearest 100,000 pounds per square inch. The actual average test value for coast Douglas fir, for example, is 1,550,000 pounds per square inch (Table 1), and this value has been rounded off to 1,600,000 pounds per square inch in Table 15. No increase is allowed for close-grained or dense material.



Curve Prepared by Forest Products Laboratory

FIG. 52. Relation of basic stress to duration of maximum load.

Effect of Duration of Load on Basic-Stress Values

The basic-stress values given in Table 15 are directly applicable to loads of long duration. In many instances, stress values adapted to shorter periods of loading are desired. In the majority of building structures, for example, maximum design loads are effective for relatively short periods. The ability of wood to absorb appreciably greater loads for shorter periods of time is illustrated in Fig. 52.[10] Current working-stress recommendations of the National Lumber Manufacturers Association[11] take advantage of the increased basic-stress values associated with *normal loading conditions.*

---

[10] "Procedure for determining permissible durations for less-than-maximum loads may be illustrated by the following example: Suppose 7 days cumulative duration is assumed for some infrequently repeated live load at maximum design level; the stress chosen for this condition is about 135 percent of the safe stress for permanent loading. Loading at 15 percent below the maximum design level would result in a stress 115 percent of that for permanent loading (85 percent of 135 is 115). That stress would be

THE BASIS FOR STRUCTURAL LUMBER GRADES

The purpose of structural grades of lumber is to provide material of uniform strength to which appropriate working stresses may be assigned for a particular type of use in construction. At one time, engineering handbooks contained a single working-stress value for each species in common structural use, and no indication of quality was given. Prior to 1929, published grading rules for structural material with assigned working-stress values had been issued for only a few species. Without an orderly basis for classifying structural lumber and evaluating its strength characteristics, the user ran the risk of poor construction by arbitrarily assigning excessively high working stresses or possibly utilized unnecessarily large sizes by accepting overly conservative working-stress values.

The most important factors that influence the strength of structural material are the size, number, and location of defects and, to some extent, the density of the wood and its moisture content during use. These factors must be considered in design or grading if maximum efficiency in utilization is to be obtained. Structural grades control defects by limiting their size, extent, and location in accordance with their effect upon strength.

Among the earliest grading rules that recognized the essential principles of structural lumber grading were those published by the U. S. Forest Service in 1912.[12] Under these rules a beam was divided into three zones: (1) the center portion of its length including the surface stressed in tension, (2) the zone stressed in compression at the opposite face of the center portion of the

---

safe for a cumulative period of about 1 year. In like manner, loading at 25 percent below maximum design level would result in a working stress about equal to that for permanent loading, and could be neglected insofar as cumulative duration is concerned." *Recommendations for basic stresses,* footnote 5.

[11] *National design specification for stress-grade lumber and its fastenings,* rev., footnote 7.

[12] McG. Cline and A. L. Heim, *Tests of structural timbers,* U. S. Dept. Agr. For. Serv. Bul. 108, Washington, 1912.

beam, and (3) the remainder of the beam chiefly subjected to shearing stresses. Large knots were permitted in the shear zone, but defects such as shake, affecting shearing resistance, were limited. Since it was known that the compressive strength of wood is reduced less than its tensile strength by a knot of given size, larger knots were permitted in the zone stressed in compression than in the tension zone. The latter provision was based on the assumption that the beam would be placed in service in a particular position and proved to be impracticable. Nevertheless, the groundwork had been laid for modern stress grading.

Subsequent recommendations,[13] based largely on work conducted at the Forest Products Laboratory, led to the adoption by the lumber industry of the provisions for structural-lumber grading published as American Lumber Standards in 1929 and their subsequent revision.[14] All major lumber manufacturers' associations now have established stress grades for structural lumber based on the principles of American Lumber Standards.[15] Stress grades are based on characteristics that are evident on visual examination of a timber and their influence with respect to its use under certain general types of loading. The grade applies to the timber as a unit, and regrading is necessary, should the piece be resawed or cross-cut prior to installation in service. Consideration is limited to factors that influence the strength of the piece.

Classification of Structural Lumber

On the basis of its use and size, structural lumber is classified as follows:

Joists and planks. Lumber of rectangular cross section, 2 inches up to but not including 5 inches in thickness and 4 inches or more in width. Grading is based on the strength in bending of the material when loaded on the narrow face as a joist or on the wide face as a plank. Such lumber may therefore be used on edge as joists or rafters, or flat as scaffold plank or factory flooring. Structural lumber of these sizes is also subjected to direct stress in tension or compression when employed as chord and web members of timber trusses.

---

[13] J. A. Newlin and R. P. A. Johnson, *Basic grading rules and working stresses for structural timbers,* U. S. Dept. Agr. Dept. Circ. 295, Washington, 1923. Also T. R. C. Wilson, *Guide to the grading of structural timbers and the determination of working stresses,* U. S. Dept. Agr. Misc. Publ. 185, Washington, 1934.

[14] *Lumber,* Simplified Practice Recommendation R16-39, U. S. Dept. Comm. Nat. Bur. Standards, Washington, 1940.

[15] See grading rules or specifications of associations listed in Table 24.

Beams and stringers. Lumber of rectangular cross section, 5 inches or more in thickness and 8 inches or more in width, graded with respect to strength in bending when loaded on the narrow face. Such material is employed as beams, girders, and stringers. Material to be used as caps and bridge ties, where bending strength is a factor, should be specified in beam and stringer grades although of dimensions more commonly considered as timbers. In applying the knot provisions of beam and stringer grades to such material, the limitations placed on narrow faces are applicable to horizontal faces (if vertical loading is assumed), and those stated for wide faces apply to the vertical faces of caps or bridge ties.

Posts and timbers. Lumber of square or approximately square cross section, 5 by 5 inches or larger,[16] graded primarily for use as posts or columns supporting a longitudinal load. Such lumber is also adapted to use as sills and other miscellaneous purposes for which bending strength is not especially important.

Standard Dimensions

For joists and planks the thickness after surfacing is limited to 3/8 inch less than the nominal dimension. A 3/8-inch limit below nominal dimension is also placed on widths up to 7 inches. For widths of 8 inches or more, the surfaced width may be 1/2 inch less than nominal. Thus a surfaced 4-by-10-inch joist actually measures 3 5/8 by 9 1/2 inches.

After surfacing, the dimensions of beams and stringers may be 1/2 inch less than nominal in thickness and width.

Standard surfaced posts and timbers in sizes less than 6 by 6 inches may be 3/8 inch undersize in each dimension, and, in sizes 6 by 6 inches or greater, 1/2 inch less than nominal size in each dimension.

[16] The minimum size of posts and timbers is defined as 4 by 4 inches in *Guide to the grading of structural timbers,* footnote 13.

Basic Provisions for Grading Rules for Structural Lumber[17]

The principal defects which are limited in structural grades are knots, slope of grain, shakes, and checks. Consideration is also given to the exclusion of decay and of exceptionally low-density weak wood. Specific rules are stated for the estimation of density in southern yellow pine and Douglas fir.

WEIGHT

No pieces of exceptionally light weight are permitted in any grade.

SOUND WOOD

Structural grades of lumber contain only sound wood, free from any form of decay, incipient or advanced, except that peck is permitted to the same extent as holes.[18]

DEFINITIONS OF FACES AND EDGES

The faces of a piece of dimension or of a timber are the four longitudinal surfaces of the piece, sometimes further designated as "wide" faces or "narrow" faces.

In a piece of lumber graded for use in bending, wide faces are taken as vertical faces, and narrow faces as horizontal faces, unless otherwise noted.

The edges of a piece of lumber are understood to be the narrower faces, and the sides the wider faces. In describing the location of knots and other defects in structural material, however, the edges of a given face are understood to be the intersection of two adjacent faces.

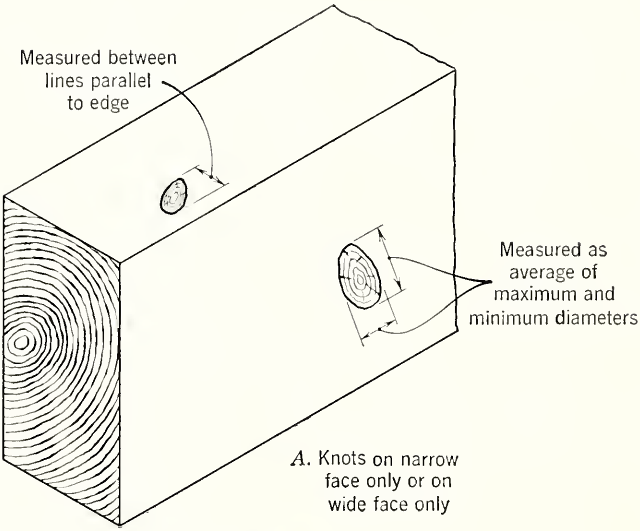
KNOTS

The influence of a knot is determined by its size, location, and the type of stress to which the zone in which it occurs may be subjected. Knot limitations and their method of measurement

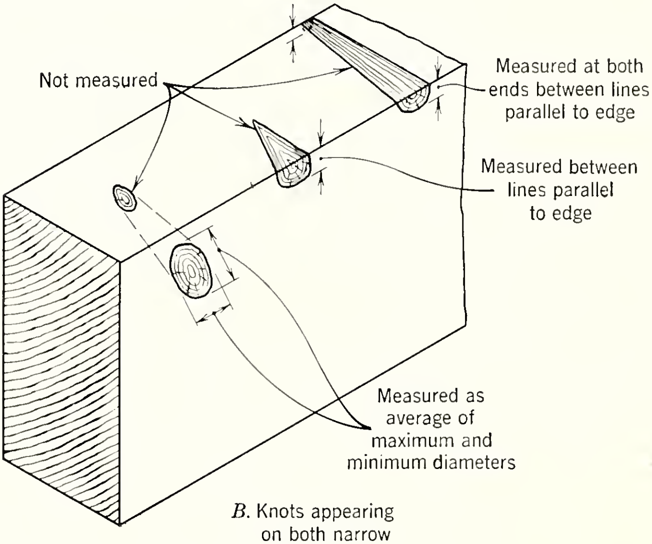
---

[17] *Lumber,* Simplified Practice Recommendation R16-39, footnote 14.

[18] This statement excluding decay is applicable to grades of structural lumber whose strength exceeds 50 percent that of clear wood. In recommending provisions for the grading of structural dimension (joist and plank) in grades having less than 50 percent of the strength of clear material, pieces containing a limited amount of decay are acceptable. For. Prod. Lab. Rept. R1225, Madison, 1940, Supplement 1 to U. S. Dept. Agr. Misc. Publ. 185.


Measured between lines parallel to edge
Measured as average of maximum and minimum diameters

A. Knots on narrow face only or on wide face only


Not measured
Measured at both ends between lines parallel to edge
Measured between lines parallel to edge
Measured as average of maximum and minimum diameters

B. Knots appearing on both narrow and wide faces

Fig. 53. Measurement of knots in joist and plank.

vary accordingly in joists and planks, beams and stringers, and posts and timbers. In structural lumber grades no distinction is made between intergrown knots, encased knots, or knot holes. Observations at the Forest Products Laboratory have shown that intergrown knots reduce strength fully as much as encased knots or knot holes. Cluster knots are not permitted in structural grades.

Joists and Planks. The only knots measured on narrow faces (except as noted in the next paragraph) are those that do not appear on wide faces. Their size is measured as the distance between lines enclosing the knot and parallel to the edges of the piece as shown in Fig. 53.

On wide faces the size of knot is its average diameter. However, a knot that crosses a corner of a side-cut piece and contains the intersection of adjacent faces is measured only on the end appearing on the face containing the shorter portion, and knots that extend entirely across a face are measured at both ends, both measurements between lines enclosing the knot and parallel to the edges of the piece (Fig. 53).

The size of knots on narrow faces and at the edges of wide faces may increase proportionately from the size permitted in the middle third of the length to twice that size at the ends of the piece, as long as it does not exceed the size permitted at the center line of the wide face throughout the length of the piece (Fig. 54). The size of knots on wide faces may increase proportionately from the size permitted at the edge to the size permitted along the center line (Fig. 54).

On the narrow faces of a joist, the method of measurement is an expression of the amount of highly stressed surface fiber whose continuity is interrupted by the knot. The effect of such a knot on the strength of a joist is approximately equal to a reduction in width of the narrow face equivalent to the size of the knot.

In joist dimensions a knot appearing on a wide face is likely to interrupt the continuity of fiber throughout a considerable portion of the thickness, thus justifying the use of average diameter, rather than minimum diameter, in estimating the weakening effect of the knot. This method of measurement excludes damaging spike knots since it is applied to them as well as to round or oval knots. As far as strength as a joist is concerned, knots on wide faces reduce strength most when located along the top and bottom edges, and the limitation of knots in these locations to a size smaller than that permitted along the center line is established on this basis. The reduction in strength due to a knot near the edge of a wide face is approximately equivalent to reducing the depth of the joist by an amount equal to the size of the knot. (Strength of a joist is proportional to its net depth squared.) For most common knot sizes, the reduction in strength is roughly twice the ratio of size of knot to width of face.

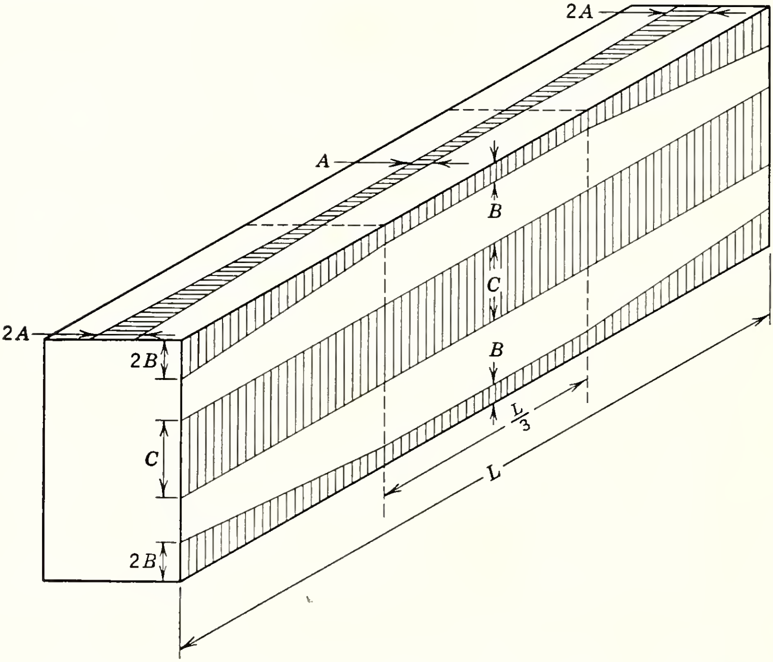


FIG. 54. Relative size of knots permitted in various portions of joist-and-plank or beam-and-stringer grades. *A*. Maximum size on narrow face in middle third of length. *B*. Maximum size at edge of wide face in middle third of length. *C*. Maximum size at center line of wide face. (In beam and stringer sizes *A* and *B* are equal.)

Considering the use of the same piece as a plank, knot limitations at the edges of wide faces are more severe than would be required, since theoretically the size applying along the center line of the wide face would apply across the entire width when used as plank. It has been found, however, that under practically all conditions of use, knots along the edges of planks are more objectionable than knots along the center line. The same knot limitations are applied, therefore, to material to be used either as joist or plank, and the same working stresses assigned for use either on edge or flat.

The increase in size of knots permitted on the narrow faces and at the edges of wide faces beyond the middle third of the length of the piece reflects the reduced stresses in tension and compression in these areas in both joists and planks when loaded in bending between two end supports.

The frequency of knots on any face within the middle half of the length of a piece is limited, for a 16-foot piece, by an aggregate size 4½ times that of the largest knot permitted on that face.

When used as members in direct stress as in timber trusses, knot limitations specified for the middle one-third or one-half length should be applied throughout the entire length of the piece.[19]

Beams and Stringers. On a narrow face the size of a knot is measured (as in joists and planks) between lines enclosing the knot and parallel to the edges of the piece. When the same knot appears on both a narrow face and the adjacent one fourth of a wide face, it is measured on the wide face only, and its size is expressed as its smallest diameter (Fig. 55). The size of a knot on a wide face is its smallest diameter.

Measurements of knots crossing corners of side-cut pieces and of spike knots extending entirely across faces are identical with those stated under joists and planks (Fig. 55).

Sizes of knots permitted beyond the middle third of the length and between the edge and center line of a wide face at any cross section are increased as stated under joists and planks (Fig. 54).

In structural lumber of beam and stringer dimensions, the proportion of the cross section influenced by a knot of given dimensions is not so great as in the case of joist and plank. Minimum diameter is therefore used in expressing the size of a knot on a wide face. One of the best examples illustrating the justification

---

[19] In recommending provisions for structural dimension (joist and plank) in grades having less than 50 percent of the strength of clear material, knots and slope of grain are limited to the same value throughout their length in order that material cut to shorter lengths after grading may not be lowered in grade. Supplement 1 to U. S. Dept. Agr. Misc. Publ. 185, footnote 18.

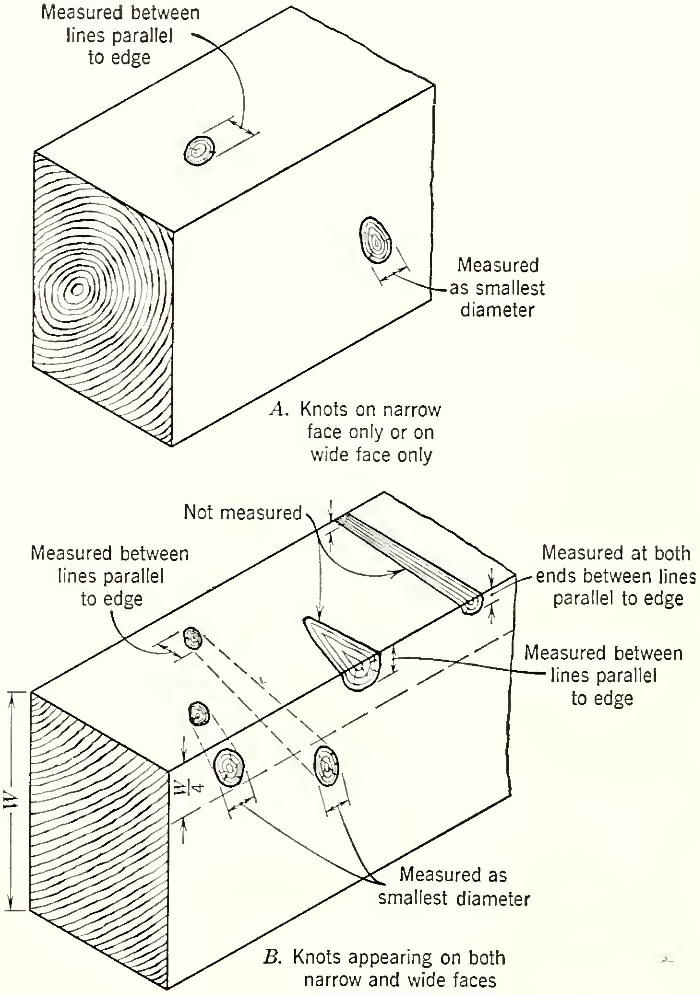

Measured between lines parallel to edge
Measured as smallest diameter
A. Knots on narrow face only or on wide face only
Not measured
Measured between lines parallel to edge
Measured at both ends between lines parallel to edge
Measured between lines parallel to edge
W
$\frac{W}{4}$
Measured as smallest diameter
B. Knots appearing on both narrow and wide faces

Fig. 55. Measurement of knots in beams and stringers.

for taking the smallest diameter on a vertical face is the splitting of a boxed heart beam into two pieces. The long spike knots exposed in this way would be no more injurious to the strength of the two resulting pieces when loaded as beams than is the single knot in the boxed-heart piece.

Even near the edges of a wide face where stresses are most severe, reduction in strength is in most cases approximately proportional to the ratio of knot size to width of face. Since there is a greater proportional distortion of grain around a large knot than around a smaller one, however, allowable knot sizes for any grade are increased proportionately to width of face only up to a 6-inch width of narrow face and 12-inch width of wide face. Beyond these dimensions, the increase in size of knot permitted is determined by multiplying the square root of the ratio of face width to maximum width of face for which increase in knot size is proportional, by the size of knot permitted at the 6- or 12-inch width. For example, in a 16-inch-wide vertical face of a grade permitting a 3-inch knot in a 12-inch face, permissible knot size would be $\sqrt{16/12} \times 3$, or approximately 3½ inches.

Frequency of knots is limited as for joists and planks except that the aggregate size of knots permitted on any face in the middle half of a 16-foot piece is 4 times the size of maximum permissible knot.

Limitations specified on the basis of middle third or middle half of the length of a piece are based on the assumption of a single span and are applicable to the middle two thirds of the length over a double span and to the entire length of pieces used over three or more spans.

Posts and Timbers. The size of a knot at any point on any face is its average diameter (Fig. 56), except that knots that cross corners of side-cut pieces or extend entirely across a face are measured as stated under joist and plank. Average diameter is a measure of the reduction in effective cross section of the piece.

The sum of the sizes of all knots in any 6-inch length of a piece is limited to 2 times the maximum size of allowable knot. Two knots of maximum size are not allowed in the same 6-inch length of any one face.

Reduction in strength due to knots in posts and timbers is approximately in direct proportion to the ratio of knot size to face width up to a 12-inch width of face. Beyond this, increased knot sizes are determined by applying the square root of the ratio of face width to 12 inches as a multiplier to the size allowed in a 12-inch width of face.

SLOPE OF GRAIN

Slope of grain is measured over a sufficient distance to assure determination of the general slope, disregarding short local deviations of grain. In joists and planks and beams and stringers, slope of grain limitations are placed on the middle half of the length of the piece. These limitations are based on the assumption that the member will be loaded in bending on a single span. Such limitations should be applied to the middle two thirds of length when used over double spans and to the entire length when used over three or more spans. They should also be applied to the entire length when joist and plank are subjected to direct stress as in truss members.[20]

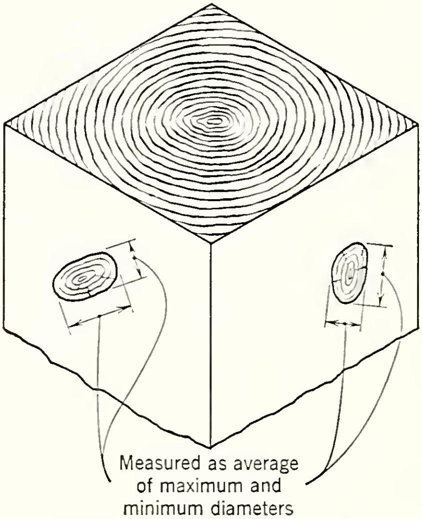


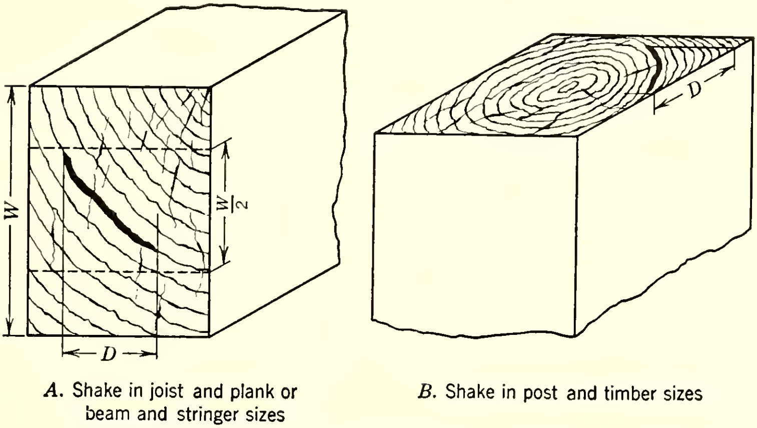
FIG. 56. Measurement of knots in posts and timbers.

SHAKES, CHECKS, AND SPLITS

Shakes reduce the area of a beam acting in resistance to shear, and the limitations placed on shake are based on this reduction. Checks and splits are limited on the same basis as shakes, and no combination of shakes, checks, and splits is permitted that would reduce strength to a greater extent than would the allowable size of shake alone. Shake in unseasoned members loaded in bending is assumed to reduce shearing stress in direct proportion to its extent. A greater amount of shake is permitted in seasoned material, made up for by the increased resistance of the remaining cross section when seasoned. In seasoned materials of joist and plank, beam and stringer grades, shake is permitted in direct proportion of increase from one-ninth the width of the piece in a grade of the strength of unseasoned clear wood to five-ninths the width of the piece in a grade having one-half the strength of unseasoned clear wood.

---

[20] See footnote 19.



A. Shake in joist and plank or beam and stringer sizes

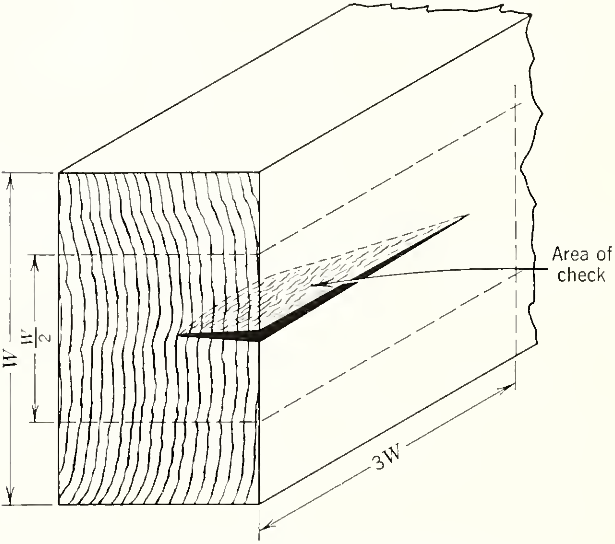
B. Shake in post and timber sizes

Fig. 57. Measurement of shakes in structural lumber.

Shakes are measured on the ends of a piece. In joists and planks, beams and stringers, only those shakes occurring within the middle half of the depth (wide dimension) are considered. The size of a shake is the distance between lines enclosing the shake and parallel to the wide faces of the piece (Fig. 57). Permissible size is determined by the width of the narrow face.

In posts and timbers the size of a shake is the distance between lines enclosing the shake and parallel to those faces of the piece that result in the greater measurement of shake (Fig. 57).

Limitations on checks and splits in joists and planks and beams and stringers apply to both ends of the piece, but only within the middle half of its depth (width of wide face) and within 3 times its depth from the end. The size of check within this portion of a piece is its estimated area (width × length), along the horizontal section showing maximum checked area, divided by 3 times the depth of the piece (Fig. 58). When checks on two parallel faces are opposite or nearly so, the sum of their sizes is taken.



Size of check or split = area of check or split ÷ $3W$
Joist and plank, beam and stringer sizes: Measured only in middle half of depth within $3W$ from end.
Post and timber sizes: Measured from any surface within $3W$ from end of piece.

Fig. 58. Measurement of checks and splits in structural lumber.

In posts and timbers, the size of a check within 3 times the width of a piece from either end is its estimated area, taken along the longitudinal section showing maximum checked area, divided by 3 times the width of the piece.

Pitch Pockets

Pitch pockets are ordinarily not defects in a structural grade. Numerous pitch pockets, however, indicate a general weakness or lack of bond, and such a piece should be carefully inspected for shakes.

WANE

Wane is limited by such considerations as bearing area, nailing edge, and appearance, rather than by effect on strength. The percentage reduction in strength resulting from wane toward the center of a beam is about double the percentage reduction in cross-sectional area. No combination of wane and knots is permitted that would reduce the strength more than the maximum allowable knot. The occurrence of maximum wane and maximum knot in the same cross section at the center of a beam would be so rare, however, and the effect of the allowable maximum wane is so small a percentage of the effect of the maximum allowable knot that the additional reduction in strength beyond the effect of the knot would be slight; hence, it is usually unnecessary to give attention to combination of wane and knots. Wane is measured at the point of maximum wane on any face.

HEARTWOOD AND SAPWOOD

Heartwood and sapwood have, in general, been found by the Forest Products Laboratory to be of equal strength, and no requirement of heartwood need be made when strength alone is the governing factor. Heart requirement, when durability of untreated material under exposure is a factor, as in bridges, trestles, docks and piers, or in damp buildings or buildings in which conditions of high humidity prevail, may be specified in any grade, according to exposure and use. When preservative treatment is to be applied, there should be no restriction as to sapwood, as sapwood is easier to treat than heartwood, and a large amount is to be preferred.

DENSITY

In southern pine and Douglas fir, the proportion of summerwood furnishes a practical means of estimating density. Selection of these species for density, to the extent that dense material is commercially available, assures structural lumber of the highest character from the standpoint of strength and uniformity in strength of the clear wood.

In acceptance for density, the contrast in color between summerwood and springwood must be distinct to assure the absence of compression wood. Compression wood occasionally occurs in bands of growth rings which appear generally darker than adjacent normal wood.[21] The summerwood merges into the springwood abnormally with a gradual rather than abrupt change of color that is not normal in these species. Compression wood, although dense, is low in tensile strength for its density, exhibits a decided longitudinal shrinkage, and is undesirable in even a small part of the cross section of high-grade structural timbers.

Methods of measurement for density are given for the determination of dense grades of Douglas fir and southern yellow pine.

Dense Douglas Fir. Douglas fir of dense material averages on either one end or the other not less than six annual rings per inch, and, in addition, one-third or more summerwood measured over a 3-inch portion of a radial line located as described in the following paragraphs. The contrast in color between summerwood and springwood must be distinct. Coarse-grained material excluded by this rule is accepted as dense if averaging one-half or more summerwood.

The radial line selected for determination of density is one representative of the average growth as viewed on the cross section. In boxed-heart pieces the radial line runs from the pith to the corner farthest from the pith. When the least dimension is 6 inches or less, the 3-inch portion of the line begins at a distance of 1 inch from the pith. When the least dimension is more than 6 inches, the 3-inch portion of the line begins at a distance from the pith equal to one-fourth the least dimension.

In side-cut pieces the center of the 3-inch radial line is at the center of the end of the piece.

If a 3-inch radial line cannot be obtained, measurement is made over as much of a 3-inch portion as is available.

Dense Southern Pine. Southern pine of dense material averages on either one end or the other not less than six annual rings per inch, and, in addition, one-third or more summerwood, measured over a radial line as described in the following. The contrast in color between summerwood and springwood must be distinct. Coarse-grained material excluded by this rule is accepted as dense if it averages one-half or more summerwood.

The radial line is selected to be representative of the growth shown on the cross section. In boxed-heart pieces the measurement is made over the third, fourth, and fifth inches from the pith along this radial line.

---

[21] See section on Defects, page 122.

In pieces containing the pith, but not a 5-inch radial line, which are less than 2 by 8 inches in section or less than 8 inches in width, that do not show over 16 square inches on the cross section, the inspection is applied to the second inch from the pith. In larger pieces that do not show a 5-inch line, the inspection applies to the 3 inches farthest from the pith.

In cases where timbers do not contain the pith and it is impossible to locate it with any degree of accuracy, the same inspection is made over 3 inches on an approximate radial line beginning at the edge nearest the pith in material over 3 inches in thickness, and on the second inch nearest the pith in pieces 3 inches or less in thickness.

Close Grain

Selection for rate of growth is not so great an assurance of high strength as selection for percentage of summerwood, but for many purposes selection for rate of growth in Douglas fir and redwood will assure material of suitable type.

Close-Grained Douglas Fir. Douglas fir of close grain averages on either one end or the other not less than 6 nor more than 20 annual rings per inch, measured over a 3-inch portion of a radial line as described previously under the density rule. Pieces averaging 5 rings or more than 20 rings per inch are accepted as close-grained if they contain one-third or more summerwood.

Close-Grained Redwood. Close-grained redwood averages on either one end or the other not less than 10 nor more than 35 annual rings per inch, measured over a 3-inch portion of a radial line, as described under the density rule for Douglas fir.

Strength Ratios

The **strength ratio** of a structural lumber grade is the percentage ratio of its strength to that of clear wood. In other words it is the ratio, expressed as a percentage, of the working stress of a grade to the basic stress for clear material of the species, if comparable conditions of loading are assumed. A particular grade may be characterized by different strength ratios for different types of stress as, for example, in the ratios for stress in extreme fiber in bending and maximum shearing stress in grades intended for use as beams.

Systematic studies of the influence of various defects on the strength of wood furnish the basis for the strength ratios presented in Tables 16 through 21. Defect limitations in structural grades of lumber to which specific working-stress values are assigned have been established on the basis of these strength ratios. When the limitations of a grade for two types of defect affecting the same type of stress do not produce equivalent strength ratios, the more critical defect, that is, the one corresponding to the lower strength ratio, determines the working stress assigned to the grade. Although some of the tables show defect limitations corresponding to strength ratios as low as 25 percent, current stress grades of lumber are characterized, in general, by strength ratios of approximately 50 percent or more.

Limitations on Defects in Structural Lumber Grades

The limitations prescribed for a structural lumber grade are based on its working-stress requirements and its strength ratio. The Select Structural grade of longleaf pine beams and stringers serves to illustrate the principle involved (Table 22). Since a density rule is employed in selecting material for this grade, the basic stress (Table 15) for dense southern pine, 2550 pounds per square inch, is used for *extreme fiber in bending.* In the derivation of working stresses for *normal loading conditions,*[22] the basic-stress values applicable to permanent loading are first increased by 10 percent resulting, in this case, in an adjusted basic stress of 2800 pounds per square inch. The working stress of 2400 pounds per square inch that has been assigned to this grade corresponds to a strength ratio of 86 percent (2400/2800), and is reasonably substantiated by the individual strength ratios based on knot size and slope of grain.

A working stress in *horizontal shear* of 120 pounds per square inch has been assigned to this grade. In deriving this value the basic stress in horizontal shear for dense southern pine, given in Table 15 as 190 pounds per square inch, has been subjected to an upward revision of 10 percent for normal loading (190 × 1.10 = 210), and a strength ratio of 57 percent (120/210) has

---

[22] *National design specification for stress-grade lumber and its fastenings,* rev., footnote 7.

TABLE 16. PERCENTAGE STRENGTH RATIOS FOR EXTREME FIBER IN BENDING FOR VARIOUS SIZES OF KNOTS*

Joists and Planks: Narrow Face
Beams and Stringers: Narrow Face and Edge of Wide Face

Size of Knot, in.	Width of Face, in.									
	2	3	4	5	6	8	10	12	14	16
¼	90	93	95	96	96	97	97	97	98	98
⅜	83	89	92	93	94	95	96	96	96	97
½	77	85	88	91	92	93	94	95	95	95
⅝	71	81	85	88	90	92	92	93	94	94
¾	65	76	82	86	88	90	91	92	92	93
⅞	58	72	79	83	86	88	89	90	91	91
1	52	68	76	81	84	86	88	89	89	90
1⅛	47	64	73	78	82	84	86	87	88	89
1¼	40	60	70	76	80	83	84	86	87	88
1⅜	33	56	67	73	78	81	83	84	85	86
1½	27	51	63	71	76	79	81	83	84	85
1⅝		47	60	68	74	77	80	81	83	84
1¾		43	57	66	71	75	78	80	81	83
1⅞		39	54	63	69	73	76	78	80	81
2		36	51	61	67	72	75	77	79	80
2⅛		31	48	58	65	70	73	75	77	79
2¼		26	45	56	63	68	71	74	76	77
2⅜			36	53	61	66	70	72	74	76
2½			32	51	59	64	68	71	73	75
2⅝			29		57	63	67	70	72	74
2¾			25		55	61	65	68	70	72
2⅞					53	59	63	67	69	71
3					51	57	62	65	68	70
3⅛						55	60	64	66	68
3¼						54	59	62	65	67
3⅜						52	57	61	64	66
3½						50	55	59	62	65
3⅝							54	58	61	63
3¾							52	56	59	62
3⅞							50	55	58	61
4								53	57	60
4⅛								52	55	58
4¼								50	54	57
4⅜									53	56
4½									51	54
4⅝									50	53
4¾										52
4⅞										51

* The knot sizes specified are those that apply to the middle third of the length as stated on page 225. Strength ratios of 45 percent or higher are based on nominal width of face; those below 45 percent on actual width.

Strength ratios above 50 percent from *Guide to the grading of structural timbers and the determination of working stresses*, U. S. Dept. Agr. Misc. Publ. 185, and those between 25 and 50 percent from For. Prod. Lab. Rept. R1225, Supplement 1 to U. S. Dept. Agr. Misc. Publ. 185.

TABLE 17. PERCENTAGE STRENGTH RATIOS FOR EXTREME FIBER IN BENDING FOR VARIOUS SIZES OF KNOTS*

Joists and Planks: Edge of Wide Face

Size of Knot, in.	Width of Face, in.										
	4	6	8	10	12	14	16	18	20	22	24
1/4	90	93	95	96	97	97	97	97	97	97	98
3/8	84	89	92	93	94	95	95	95	96	96	96
1/2	78	85	89	91	92	93	93	94	94	94	95
5/8	73	81	86	89	90	91	92	92	93	93	93
3/4	68	78	83	86	88	89	90	91	91	91	92
7/8	63	74	80	84	87	88	88	89	89	90	90
1	58	71	77	82	85	86	87	87	88	89	89
1 1/8	53	67	75	79	83	84	85	86	86	87	88
1 1/4	49	64	72	77	81	82	83	84	85	86	86
1 3/8	40	60	69	75	79	80	82	83	83	84	85
1 1/2	36	57	67	73	77	79	80	81	82	83	84
1 5/8	32	54	64	71	75	77	78	80	81	81	82
1 3/4	28	51	62	69	74	75	77	78	79	80	81
1 7/8		48	59	67	72	74	75	77	78	79	80
2		45	57	65	70	72	74	75	76	77	78
2 1/8		40	55	63	68	70	72	74	75	76	77
2 1/4		37	52	61	67	69	71	72	73	75	76
2 3/8		34	50	59	65	67	69	71	72	73	74
2 1/2		32	48	57	63	66	68	69	71	72	73
2 5/8		29	46	55	62	64	66	68	69	71	72
2 3/4		27	42	53	60	63	65	66	68	69	71
2 7/8		25	40	51	58	61	63	65	67	68	69
3			38	50	57	60	62	64	65	67	68
3 1/8			36	48	55	58	60	62	64	66	67
3 1/4			34	46	54	57	59	61	63	64	66
3 3/8			32	39	52	55	58	60	62	63	65
3 1/2			30	37	51	54	56	58	60	62	63
3 5/8			28	35	49	52	55	57	59	61	62
3 3/4			26	34	48	51	54	56	58	60	61
3 7/8				33	46	50	52	55	57	58	60
4				31	45	48	51	53	55	57	59
4 1/8				30	42	47	50	52	54	56	58
4 1/4				28	40	46		51	53	55	57
4 3/8				27	39	43		50	52	54	55
4 1/2				25	37	41			51	53	54
4 5/8					36	40			50	51	53
4 3/4					35	39				50	52
4 7/8					33	37					51
5					32	36					50
5 1/8					31	35					
5 1/4					30	34					
5 3/8					29	33					
5 1/2					28	32					
5 5/8					26	30					
5 3/4					25	29					
5 7/8						28					
6						27					
6 1/8						26					
6 1/4						25					

* The knot sizes specified are those that apply to the middle third of the length, as stated on page 225. Strength ratios of 45 percent or higher are based on nominal width of face; those below 45 percent on actual width.

Strength ratios above 50 percent from *Guide to the grading of structural timbers and the determination of working stresses,* U. S. Dept. Agr. Misc. Publ. 185, and those between 25 and 50 percent from For. Prod. Lab. Rept. R1225, Supplement 1 to U. S. Dept. Agr. Misc. Publ. 185.

TABLE 18. PERCENTAGE STRENGTH RATIOS FOR EXTREME FIBER IN BENDING AND COMPRESSION PARALLEL TO GRAIN FOR VARIOUS SIZES OF KNOTS*

Beams and Stringers, Joists and Planks: Center Line of Wide Face.
Strength Ratios for Stress in Extreme Fiber in Bending
Posts and Timbers: Any Point on Any Face. Strength Ratios for Stress in Compression Parallel to Grain

Size of Knot, in.	Width of Face, in.											
	4	5	6	8	10	12	14	16	18	20	22	24
¼	95	96	96	97	98	98	98	98	99	99	99	99
½	88	91	92	94	95	96	96	97	97	97	97	97
¾	82	86	88	91	93	94	94	95	95	95	96	96
1	76	81	84	88	90	92	93	93	93	94	94	94
1¼	70	76	80	85	88	90	91	91	92	92	93	93
1½	63	71	76	82	85	88	89	89	90	91	91	91
1¾	57	66	71	79	83	86	87	88	88	89	89	90
2	51	61	67	75	80	84	85	86	87	87	88	88
2¼	45	56	63	72	78	82	83	84	85	86	86	87
2½	32	51	59	69	75	79	81	82	83	84	85	85
2¾	25		55	66	73	77	79	80	82	82	83	84
3			51	63	70	75	77	79	80	81	82	83
3¼			47	60	68	73	75	77	78	79	80	81
3½			39	57	65	71	73	75	76	78	79	80
3¾			34	54	63	69	71	73	75	76	77	78
4			29	50	60	67	69	71	73	74	76	77
4¼			25	47	58	65	67	70	71	73	74	75
4½				41	55	63	66	68	70	71	73	74
4¾				37	53	61	64	66	68	70	71	72
5				34	50	59	62	64	66	68	70	71
5¼				31	48	57	60	62	65	66	68	69
5½				27	45	54	58	61	63	65	66	68
5¾					40	52	56	59	61	63	65	66
6					37	50	54	57	59	61	63	65
6¼					35	48	52	55	58	60	62	63
6½					32	46	50	53	56	58	60	62
6¾					29	42	48	52	54	57	59	60
7					27	39	46	50	53	55	57	59
7¼						37	43		51	53	56	57
7½						35	42			52	54	56
7¾						33	40			50	53	55
8						31	38				51	53
8¼						29	36					52
8½						26	34					50
8¾							32					
9							30					
9¼							28					
9½							26					

* The knot sizes specified apply to the middle third of the length of beams, stringers, joists, and planks as stated on page 225. Strength ratios of 45 percent or higher are based on nominal width of face; those below 45 percent on actual width.

Strength ratios above 50 percent from *Guide to the grading of structural timbers and the determination of working stresses*, U. S. Dept. Agr. Misc. Publ. 185, and those between 25 and 50 percent from For. Prod. Lab. Rept. R1225, Supplement 1 to U. S. Dept. Agr. Misc. Publ. 185.

been used. This is in good agreement with the shake and check limitations provided in the grade description.

This grade also carries an assigned allowable stress in *compression parallel to grain* of 1750 pounds per square inch, representing a strength ratio of 94 percent when compared with the revised basic stress of 1870 pounds per square inch obtained by a 10 percent upward adjustment of the value (1700 pounds per square inch) shown for compression parallel to grain in Table 15.[23,24] Comparison of this strength ratio with the 86 percent

TABLE 19. PERCENTAGE STRENGTH RATIOS FOR STRESS IN EXTREME FIBER IN BENDING AND COMPRESSION PARALLEL TO GRAIN FOR VARIOUS SLOPES OF GRAIN*

Beams and Stringers, Joists and Planks: Extreme Fiber in Bending
Posts and Timbers: Compression Parallel to Grain

Slope of Grain	Extreme Fiber in Bending	Compression Parallel to Grain
1 in 20	100	100
1 in 18	85	100
1 in 16	80	100
1 in 15	76	100
1 in 14	74	87
1 in 12	69	82
1 in 10	61	74
1 in 8	53	66
1 in 6	..	56

* Slopes of grain specified are those that apply to the middle half of the length of beams and stringers and of joists and planks as stated on page 230; they apply throughout the length of post and timber grades.

Strength ratios from *Guide to the grading of structural timbers and the determination of working stresses,* U. S. Dept. Agr. Misc. Publ. 185.

---

[23] To qualify for use in compression parallel to the grain with assigned working-stress values, beam and stringer and joist and plank grades must meet the following provisions: The sum of the sizes of all knots in any 6 inches of length may not exceed twice the maximum permissible size of knot. Two knots of maximum permissible size may not be located within the same 6 inches of length on any face. *National design specification,* footnote 7.

[24] Although, in principle, a 10 percent upward adjustment of basic stress in compression parallel to grain on the basis of normal loading conditions rather than permanent loading is recognized in the *National design specification,* rev. 1948, in actual practice a 20 percent increase over basic-stress values of Table 15 has been assumed in the derivation of working stresses for established stress grades. See footnote 7.

ratio indicated by knot limitations along the center line of the wide face (equivalent to the largest knots permissible at any point in the piece) illustrates a somewhat less conservative practice in the assignment of working-stress values in compression parallel to grain. Knot limitations rather than slope of grain obviously govern the assigned working stress in compression parallel to grain since, as shown in Table 19, a grain slope of 1 in 18 corresponds to a strength ratio of 100 percent in compression parallel to the grain. In establishing strength ratios in compression parallel to grain in beam and stringer or joist and plank grades, the strength ratios in Table 21 corresponding to the allowable sizes of shakes or checks have not been considered.

In joist and plank grades, defects that affect stress in extreme fiber in bending are generally larger in proportion to width of face than in beam and stringer grades of equivalent working stress.

The 2400 f grade of Select Structural longleaf pine joist and plank permits the defects with corresponding strength ratios indicated in Table 23.

Although a strength ratio of 74 percent in extreme fiber in bending is indicated by the defect limitations specified, the strength ratio assigned to the grade is actually 86 percent $\left(\frac{2400}{2550 \times 1.10}\right)$.

The basis for so modifying the calculated strength ratios of lumber of joist and plank dimensions lies in the increased strength of such material as a result of drying. According to U. S. Dept. of Agr. Misc. Publ. No. 185, "For material 4 inches or less in thickness to be used where continuously dry, the strength ratio for stress in extreme fiber . . . (is) increased by one half of its excess over 50 percent. If, for example, the strength ratio for stress in extreme fiber in bending for a grade of joist and plank is 66⅔ percent, and the material is to be used where it will be continuously dry, the working stress is 75 percent of the basic stress for the species under consideration." Similar provisions are made for material 4 inches or less in thickness when stressed in compression parallel to the grain. In the foregoing example of Select Structural longleaf pine joist and plank, the increase from an indicated strength ratio of 74 percent is cal-

TABLE 20. PERCENTAGE STRENGTH RATIOS FOR STRESS IN HORIZONTAL SHEAR FOR VARIOUS SIZES OF SHAKES AND CHECKS*

Beams and Stringers, Joists and Planks

Size of Shake or Check, in.	Green Material, Width of Piece, in.										Seasoned Material, Width of Piece, in.									
	2	3	4	5	6	8	10	12	14	16	2	3	4	5	6	8	10	12	14	16
¼	90	93	95	96	96	97	98	98	98	99	100	100	100	100	100	100	100	100	100	100
⅜	83	89	92	93	94	96	97	97	98	98	94	100	100	100	100	100	100	100	100	100
½	77	85	88	91	92	94	95	96	97	97	87	95	100	100	100	100	100	100	100	100
⅝	71	81	85	88	90	93	94	95	96	96	80	91	96	99	100	100	100	100	100	100
¾	65	76	82	86	88	91	93	94	95	96	73	86	93	97	99	100	100	100	100	100
⅞	58	72	79	83	86	90	92	93	94	95	66	81	89	94	97	100	100	100	100	100
1	52	68	76	81	84	88	90	92	93	94	59	77	85	91	94	99	100	100	100	100
1⅛	48	64	73	78	82	86	89	91	92	93	52	72	82	88	92	97	100	100	100	100
1¼	25	60	70	76	80	85	88	90	91	92	45	67	78	85	90	95	99	100	100	100
1⅜		56	67	73	78	83	87	89	90	92	20	62	75	82	87	94	97	100	100	100
1½		51	63	71	76	82	85	88	90	91		58	71	80	85	92	96	99	100	100
1⅝		47	60	68	74	80	84	87	89	90		53	68	77	83	90	95	98	100	100
1¾		35	57	66	71	79	83	86	88	89		48	64	74	80	88	93	96	99	100
1⅞		30	54	63	69	77	82	85	87	88		34	61	71	78	87	92	95	98	100
2		25	51	61	67	75	80	84	86	88		29	57	68	76	85	90	94	97	99
2⅛			48	58	65	74	79	83	85	87			54	66	73	83	89	93	96	98
2¼			39	56	63	72	78	82	84	86			50	63	71	81	88	92	95	97
2⅜			36	53	61	71	77	81	83	85			47	60	69	80	86	91	94	96
2½			32	51	59	69	75	79	82	85			37	57	66	78	85	89	93	95
2⅝			29		57	68	74	78	81	84			33	54	64	76	83	88	92	94
2¾			25		55	66	73	77	81	83			29	52	62	74	82	87	91	93
2⅞					53	65	72	76	80	82			25		59	73	81	86	90	93
3					51	63	70	75	79	81					57	71	79	85	89	92

3¼	60	68	73	77	80	52	67	76	82	87	90
3½	57	65	71	75	78	48	64	74	80	85	88
3¾	54	63	69	73	77		60	71	78	83	86
4	50	60	67	72	75		57	68	75	81	85
4¼		58	65	70	74		53	65	73	79	83
4½		55	63	68	72		50	62	71	77	81
4¾		53	61	66	71			59	68	75	79
5		50	59	65	69			57	66	73	78
5¼			57	63	67			54	64	71	76
5½			54	61	66			51	61	69	74
5¾			52	59	64				59	67	72
6			50	57	63				57	65	71
6¼				56	61				54	63	69
6½				54	60				52	61	67
6¾				52	58				50	59	65
7				50	56					57	64
7¼					55					55	62
7½					53					53	60
7¾					52					51	58
8					50						56
8¼											55
8½											53
8¾											51
9											49

* The sizes of shake and check specified are measured as stated on pages 231–2. Strength ratios of 45 percent or higher are based nominal width of piece, those below 45 percent, on actual width.

Strength ratios above 50 percent from *Guide to the grading of structural timbers and the determination of working stresses*, U. S. Dept. Agr. Misc. Publ. 185, and those between 25 and 50 percent from For. Prod. Lab. Rept. R1225, Supplement 1 to U. S. Dept. Agr. Misc. Publ. 185.

Table 21. Percentage Strength Ratios for Stress in Compression Parallel to Grain for Various Sizes of Shakes and Checks*

Posts and Timbers

Size of Shake or Check, in.	Green Material, Width of piece, in.						Seasoned Material, Width of piece, in.					
	4	5	6	8	10	12	4	5	6	8	10	12
¾	100	100	100	100	100	100	100	100	100	100	100	100
1	95	100	100	100	100	100	100	100	100	100	100	100
1¼	87	95	100	100	100	100	100	100	100	100	100	100
1½	79	89	95	100	100	100	92	100	100	100	100	100
1¾	72	82	89	98	100	100	84	95	100	100	100	100
2	64	76	84	94	100	100	76	88	97	100	100	100
2¼	56	70	79	90	97	100	68	82	91	100	100	100
2½	48	63	74	87	94	99	61	76	86	99	100	100
2¾		57	69	83	91	97	53	70	81	95	100	100
3		51	63	79	88	94	45	63	76	91	100	100
3¼			58	75	85	92		57	71	87	97	100
3½			53	71	82	89		51	65	83	94	100
3¾			48	67	79	86			60	80	91	99
4				63	75	84			55	76	88	96
4¼				59	72	81			50	72	85	94
4½				55	69	79				68	82	91
4¾				51	66	76				64	79	88
5					63	73				60	75	86
5¼					60	71				56	72	83
5½					57	68				52	69	81
5¾					54	65				48	66	78
6					50	63					63	75
6¼						60					60	73
6½						58					57	70
6¾						55					54	68
7						52					50	65
7¼						50						62
7½												60
7¾												57
8												55
8¼												52
8½												49

* The sizes of shake and check specified are measured as stated on pages 231–2. Strength ratios are based on nominal width of piece.

Strength ratios from *Guide to the grading of structural timbers and the determination of working stresses*, U. S. Dept. Agr. Misc. Publ. 185.

Table 22. Grade: 2400 f (Select Structural) Longleaf Pine Beams and Stringers

Maximum Slope of Grain—1 in 18; Strength Ratio 85 percent*

Nominal Width of Face, in.	Maximum Permissible Size of						
	Knots				Shakes, Checks, and Splits		Wane, in.
	Within Middle Third of Length on Narrow Face or at Edge of Wide Face		Along Center Line of Wide Face				
	In.	Strength Ratio, %†	In.	Strength Ratio, %‡	In.	Strength Ratio, %§	
5	¾	86	...	..	2⅛	58	None permitted
6	⅞	86	⅞	86	2½	59	
8	1	86	1⅛	86	3⅜	57	
10	1⅛	86	1⅜	86	4¼	58	
12	1¼	86	1¾	86	5⅛	58	
14	1¼	87	1⅞	86	5⅞	58	
16	1⅜	86	2	86	6¾	58	
18	...	..	2⅛	86	...	..	

* From Table 19.

† From Table 16.

‡ From Table 18.

§ From Table 20.

culated as 74 + (74 − 50)/2, or 86 percent. It is evident that, by this means of adjustment, greater consideration is given to the benefits of seasoning on strength experienced by the higher grades of lumber. No increase is permitted for a grade of 50 percent or lower-strength ratio. No increase for seasoning is made in allowable shear-stress values.

As originally developed, all grades were considered as having a 100 percent strength ratio in compression perpendicular to the grain. Bearing strength across the grain is not significantly affected by defects of the type permitted in structural lumber grades. In actual practice, all established stress grades have been arbitrarily assigned working stresses in compression perpendicular to the grain applicable to *normal loading conditions* that exceed by 20 percent the basic-stress values presented in

TABLE 23. GRADE 2400 F (SELECT STRUCTURAL) LONGLEAF PINE JOISTS AND PLANKS

Maximum Slope of Grain—1 in 18; Strength Ratio 85 percent*

Nominal Width of Face, in.	Maximum Permissible Size of								
	Knots						Shakes, Checks, and Splits		Wane, in.
	Within Middle Third of Length				Along Center Line of Wide Face				
	On Narrow Face		At Edge of Wide Face						
	In.	Strength Ratio, %†	In.	Strength Ratio, %‡	In.	Strength Ratio, %§	In.	Strength Ratio, %‖	
2	½	77	...	..	...	..	⅞	58	None permitted
3	¾	76	...	..	...	..	1¼	60	
4	1	76	½	78	1	76	1⅝	60	
6	...	..	⅞	74	1½	76	...	..	
8	...	..	1⅛	75	2	75	...	..	
10	...	..	1⅜	75	2⅝	74	...	..	
12	...	..	1¾	74	3⅛	74	...	..	
14	...	..	1⅞	74	3⅜	74	...	..	
16	...	..	2	74	3⅝	74	...	..	

* From Table 19.
† From Table 16.
‡ From Table 17.
§ From Table 18.
‖ From Table 20.

Table 15.[25] Strength ratios are not applied to modulus of elasticity values. Although based on tests of clear specimens, these values have been considered reasonably applicable to material of structural-lumber quality, and constant modulus-of-elasticity values are assigned to all grades of a particular species.

WORKING STRESSES BY LUMBER GRADES

Working-stress values for various grades of structural lumber are given in Table 24.

---

[25] *National design specification,* footnote 7.

Duration of Load[26]

The values for working stress given in Table 24 are applicable to *normal loading conditions,* that is, a continuous or accumulated total period of approximately three years under maximum design load. For loads that are maintained either continuously or cumulatively at the maximum design level for many years, all working-stress values shown in Table 24 (except those for modulus of elasticity) should be reduced by 10 percent (Fig. 52). With the exception of modulus of elasticity, working-stress values may be increased by 15 percent for loads of 2 months' duration, for example, snow loads; by 25 percent for loads of 7 days' duration; by 33⅓ percent for earthquake and wind loading; and by 100 percent for impact loading. Impact loading may be disregarded if the stress resulting from impact alone does not exceed the working stress allowed for normal loading. In no case should the resulting structural member be smaller than that required for normal loads of longer duration.

Condition of Exposure

Working stresses, as indicated previously, are based on the strength of green material[27] and are generally considered applicable to service under either dry or wet conditions, as long as the wood is not subject to deterioration. Working stresses in compression perpendicular to the grain are an exception. The values in compression perpendicular to grain shown in Table 24 are based on an assumed surface-seasoned condition at the time of installation. For seasoned lumber used under continuously dry conditions these values may be increased 10 percent, and, conversely, when used under continuously wet conditions they should be reduced 10 percent. In the past,[28] ratios for the reduction of working stresses in extreme fiber in bending, compression parallel to grain, and compression perpendicular to grain have been recommended for various types of exposure

---

[26] *National design specification,* footnote 7.

[27] Working stresses for joists and planks and small posts and timbers, 4 inches or less in thickness, are derived in consideration of their improved strength when seasoned and are therefore properly applicable without modification to dry conditions of use only.

[28] *Guide to the grading of structural timbers,* footnote 13.

TABLE 24. WORKING STRESSES FOR VARIOUS GRADES OF STRUCTURAL LUMBER UNDER NORMAL LOADING CONDITIONS*

			Allowable Unit Stresses, psi				
1 Species and Commercial Grade†		2 Rules under Which Graded	3 Extreme Fiber in Bending, f, and Tension Parallel to Grain, t	4 Horizontal Shear, H	5 Compression Perpendicular to Grain, $c\perp$	6 Compression Parallel to Grain, C	7 Modulus of Elasticity, E
Ash, White							
2150 f	J.&P.	National Hardwood Lumber Association	2150	145	600	1700	1,500,000
1900 f	J.&P.-B.&S.		1900	145		1500	
1700 f	J.&P.-B.&S.		1700	145		1325	
1450 f	J.&P.-B.&S.		1450	120		1150	
1300 f	B.&S.		1300	120		1050	
1450 c	P.&T.					1450	
1200 c	P.&T.					1200	
1075 c	P.&T.					1075	
Beech							
2150 f	J.&P.	National Hardwood Lumber Association	2150	145	600	1750	1,600,000
1900 f	J.&P.-B.&S.		1900	145		1525	
1700 f	J.&P.-B.&S.		1700	145		1350	
1450 f	J.&P.-B.&S.		1450	120		1150	
1550 c	P.&T.					1550	
1450 c	P.&T.					1450	
1200 c	P.&T.					1200	
Birch							
2150 f	J.&P.	National Hardwood Lumber Association	2150	145	600	1750	1,600,000
1900 f	J.&P.-B.&S.		1900	145		1525	
1700 f	J.&P.-B.&S.		1700	145		1350	
1450 f	J.&P.-B.&S.		1450	120		1150	
1550 c	P.&T.					1550	
1450 c	P.&T.					1450	
1200 c	P.&T.					1200	
Chestnut							
1450 f	J.&P.	National Hardwood Lumber Association	1450	120	360	1200	1,000,000
1200 f	J.&P.-B.&S.		1200	120		950	
1075 c	P.&T.					1075	

Cypress, Southern							
1700 f	J.&P.–B.&S.	National Hardwood Lumber Association	1700	145	360	1425	1,200,000
1300 f	J.&P.–B.&S.		1300	120		1125	
1450 c	P.&T.					1450	
1200 c	P.&T.					1200	
Cypress, Tidewater Red							
1700 f	J.&P.–B.&S.	Southern Cypress Manufacturers' Association	1700	145	360	1425	1,200,000
1300 f	J.&P.–B.&S.		1300	120		1125	
1450 c	P.&T.					1450	
1200 c	P.&T.					1200	
Douglas Fir, Coast Region							
Dense Select Structural	J.&P.–B.&S.	West Coast Bureau of Lumber Grades and Inspection	2150	145	455	1550	1,600,000
Select Structural	J.&P.–B.&S.		1900	120	415	1450	
1700 f–Dense No. 1	J.&P.–B.&S.		1700	145	455	1325	
1450 f–No. 1	J.&P.–B.&S.		1450	120	390	1200	
1100 f–No. 2	J.&P.		1100	110	390	1075	
Dense Select Structural	P.&T.				455	1550	
Select Structural	P.&T.				415	1450	
Dense No. 1	P.&T.				455	1400	
No. 1	P.&T.				390	1200	
Douglas Fir, Inland Region							
Select Structural	J.&P.	Western Pine Association	2150	145	455	1750	1,600,000
Structural	J.&P.		1900	100	400	1400	1,500,000
Common Structural	J.&P.		1450	95	380	1250	1,500,000
Select Structural	P.&T.				455	1750	1,600,000
Structural	P.&T.				400	1400	1,500,000
Common Structural	P.&T.				380	1250	1,500,000
Elm, Rock							
2150 f	J.&P.	National Hardwood Lumber Association	2150	145	600	1750	1,300,000
1900 f	J.&P.–B.&S.		1900	145		1525	
1700 f	J.&P.–B.&S.		1700	145		1350	
1450 f	J.&P.–B.&S.		1450	120		1150	
1550 c	P.&T.					1550	
1450 c	P.&T.					1450	
1200 c	P.&T.					1200	

* From *National design specification for stress-grade lumber and its fastenings*, rev. Nat. Lbr. Mfrs. Assn., Washington, 1948.

† Abbreviations: J.&P., Joists and Planks; B.&S., Beams and Stringers; P.&T., Posts and Timbers; S.E.&S., Square Edge and Sound.

TABLE 24. WORKING STRESSES FOR VARIOUS GRADES OF STRUCTURAL LUMBER UNDER NORMAL LOADING CONDITIONS*
Continued

1 Species and Commercial Grade†		2 Rules under Which Graded	Allowable Unit Stresses, psi 3 Extreme Fiber in Bending, *f*, and Tension Parallel to Grain, *t*	4 Horizontal Shear, *H*	5 Compression Perpendicular to Grain, *c*⊥	6 Compression Parallel to Grain, *C*	7 Modulus of Elasticity, *E*
Elm, Soft							
1700 f	J.&P.	National Hardwood Lumber Association	1700	120	300	1225	1,200,000
1450 f	J.&P.–B.&S.		1450	120		1050	
1200 f	J.&P.–B.&S.		1200	120		875	
1075 c	P.&T.					1075	
Gum, Black and Red							
1700 f	J.&P.	National Hardwood Lumber Association	1700	120	360	1225	1,200,000
1450 f	J.&P.–B.&S.		1450	120		1050	
1200 f	J.&P.–B.&S.		1200	120		875	
1075 c	P.&T.					1075	
Hemlock, Eastern							
Select Structural	J.&P.–B.&S.	Northern Hemlock and Hardwood Manufacturers Association	1300	85	360	850	1,100,000
Prime Structural	J.&P.		1200	60		775	
Common Structural	J.&P.		1100	60		650	
Utility Structural	J.&P.		950	60		600	
Select Structural	P.&T.					850	
Hemlock, West Coast							
1600 f–Select Structural	J.&P.	West Coast Bureau of Lumber Grades and Inspection	1600	100	360	1100	1,400,000
1450 f–No. 1	J.&P.–B.&S.		1450	100		1075	
1100 f–No. 2	J.&P.		1100	90		850	
No. 1 Hemlock Timbers	P.&T.					1075	
Hickory							
2150 f	J.&P.–B.&S.	National Hardwood Lumber Association	2150	145	720	1725	1,800,000
1900 f	J.&P.–B.&S.		1900	145		1550	
1700 f	J.&P.–B.&S.		1700	145		1350	
1550 c	P.&T.					1550	

Hickory—*Continued*							
1450 c	P.&T.					1450	
1325 c	P.&T.					1325	
Larch							
Select Structural	J.&P.		2150	145	455	1750	
Structural	J.&P.		1900	120	415	1450	
Common Structural	J.&P.	Western Pine Association	1450	120	390	1325	1,300,000
Select Structural	P.&T.				455	1750	
Structural	P.&T.				415	1450	
Common Structural	P.&T.				390	1325	
Maple, Hard							
2150 f	J.&P.		2150	145		1750	
1900 f	J.&P.–B.&S.		1900	145		1525	
1700 f	J.&P.–B.&S.	National Hardwood Lumber Association	1700	145		1350	
1450 f	J.&P.–B.&S.		1450	120	600	1150	1,600,000
1550 c	P.&T.					1550	
1450 c	P.&T.					1450	
1200 c	P.&T.					1200	
Oak, Red and White							
2150 f	J.&P.		2150	145		1550	
1900 f	J.&P.–B.&S.		1900	145		1375	
1700 f	J.&P.–B.&S.	National Hardwood Lumber Association	1700	145		1200	
1450 f	J.&P.–B.&S.		1450	120	600	1050	1,500,000
1300 f	B.&S.		1300	120		950	
1325 c	P.&T.					1325	
1200 c	P.&T.					1200	
1075 c	P.&T.					1075	
Pecan							
2150 f	J.&P.–B.&S.		2150	145		1725	
1900 f	J.&P.–B.&S.		1900	145		1550	
1700 f	J.&P.–B.&S.	National Hardwood Lumber Association	1700	145	720	1350	1,800,000
1550 c	P.&T.					1550	
1450 c	P.&T.					1450	
1325 c	P.&T.					1325	

---

* From *National design specification for stress-grade lumber and its fastenings*, rev. Nat. Lbr. Mfrs. Assn., Washington, 1948.

† Abbreviations: J.&P., Joists and Planks; B.&S., Beams and Stringers; P.&T., Posts and Timbers; S.E.&S., Square Edge and Sound.

TABLE 24. WORKING STRESSES FOR VARIOUS GRADES OF STRUCTURAL LUMBER UNDER NORMAL LOADING CONDITIONS*
Continued

1 Species and Commercial Grade†		2 Rules under Which Graded	Allowable Unit Stresses, psi				
			3 Extreme Fiber in Bending, f, and Tension Parallel to Grain, t	4 Horizontal Shear, H	5 Compression Perpendicular to Grain, $c\perp$	6 Compression Parallel to Grain, C	7 Modulus of Elasticity, E
Pine, Norway							
Prime Structural	J.&P.	Northern Hemlock and Hardwood Manufacturers Association	1200	75	360	900	1,200,000
Common Structural	J.&P.		1100	75		775	
Utility Structural	J.&P.		950	75		650	
Pine, Southern							
Dense Select Structural	J.&P.–B.&S.	Southern Pine Inspection Bureau	2400	120	455	1750	1,600,000
Dense Structural	J.&P.–B.&S.		2000	120	455	1400	
Dense Structural S.E.&S.	J.&P.–B.&S.		1800	120	455	1300	
Dense No. 1 Structural	J.&P.–B.&S.		1600	120	455	1150	
No. 1 Dense	J.&P.		1700	150	455	1400	
No. 1	J.&P.		1450	125	390	1200	
No. 2 Dense	J.&P.		1250	100	455	1025	
No. 2	J.&P.		1100	85	390	875	
Dense Select Structural	P.&T.				455	1750	
Dense Structural	P.&T.				455	1400	
Dense Structural S.E.&S.	P.&T.				455	1300	
Dense No. 1 Structural	P.&T.				455	1150	
Pine, Southern Longleaf							
Select Structural Longleaf	J.&P.–B.&S.	Southern Pine Inspection Bureau	2400	120	455	1750	1,600,000
Prime Structural Longleaf	J.&P.–B.&S.		2000	120		1400	
Merchantable Structural Longleaf	J.&P.–B.&S.		1800	120		1300	
Structural S.E.&S. Longleaf	J.&P.–B.&S.		1800	120		1300	
No. 1 Structural Longleaf	J.&P.–B.&S.		1600	120		1150	
No. 1 Longleaf	J.&P.		1700	150		1400	
No. 2 Longleaf	J.&P.		1250	100		1025	
Select Structural Longleaf	P.&T.					1750	

Pine, Southern Longleaf—*Continued*							
Prime Structural Longleaf						1400	
Merchantable Structural	P.&T.						
Longleaf	P.&T.					1300	
Structural S.E.&S. Longleaf	P.&T.					1300	
No. 1 Structural Longleaf	P.&T.					1150	
Poplar, Yellow							
1500 f	J.&P.	National Hardwood Lumber Association	1500	110	300	1200	1,100,000
1250 f	J.&P.–B.&S.		1250	110		950	
1075 c	P.&T.					1075	
Redwood							
Dense Structural	J.&P.–B.&S.	California Redwood Association	1700	110	320	1450	1,200,000
Heart Structural	J.&P.–B.&S.		1300	95		1100	
Dense Structural	P.&T.					1450	
Heart Structural	P.&T.					1100	
Spruce, Eastern							
1450 f Structural	J.&P.	Northeastern Lumber Manufacturers Association, Inc.	1450	110	300	1050	1,200,000
1300 f Structural	J.&P.		1300	95		975	
1200 f Structural	J.&P.		1200	95		900	
Tupelo							
1700 f	J.&P.	National Hardwood Lumber Association	1700	120	360	1225	1,200,000
1450 f	J.&P.–B.&S.		1450	120		1050	
1200 f	J.&P.–B.&S.		1200	120		875	
1075 c	P.&T.					1075	

* From *National design specification for stress-grade lumber and its fastenings*, rev. Nat. Lbr. Mfrs. Assn., Washington, 1948.

† Abbreviations: J.&P., Joists and Planks; B.&S., Beams and Stringers; P.&T., Posts and Timbers; S.E.&S., Square Edge and Sound.

conducive to decay. Except for temporary construction, it would seem to be generally preferable practice to use preservative-treated wood or heartwood of naturally durable species under such conditions, retaining the working stresses of Table 24, rather than to scale down working stresses arbitrarily to allow for this hazard. Where conditions of dampness or high humidity prevail in service, proper design and maintenance are essential to eliminate or minimize deterioration resulting from decay.

APPLICATION OF WORKING STRESSES IN DESIGN

Structural uses of lumber involve the application of working stresses to the design of beams, columns, tension members, and members subjected to combined bending and axial loads. The following paragraphs are intended as an introduction to the general design methods employed.

Beams

Fiber stress in bending, horizontal-shearing stress, and deflection are the three major considerations involved in the design of beams.

Fiber Stress in Bending

The general relationship between bending moment induced by the load applied to a beam and the extreme fiber stress developed is given by the **flexure formula**:

$$M = \frac{FfI}{c} \tag{11}$$

in which M = the maximum bending moment, pound-inches, F = a form factor dependent on the shape and size of cross section; f = working stress in extreme fiber in bending, pounds per square inch; and c = distance from the neutral axis to the outermost fiber of the cross section, inches.

Form factors have been derived experimentally to account for observed influences of shape and size of cross section on the strength of beams.[29] Insofar as beams of rectangular cross section are concerned, this influence is not particularly significant, varying slightly above and below unity according to depth of beam. For example, the form factor for a beam 8 inches deep is 0.93, and that for a beam 1 inch deep is 1.02. Such variation has been explained on the basis of a supporting action of lesser-stressed underlying fibers to those more highly stressed fibers at the surface of the member. In practice, the form factor for rectangular sections is in most cases considered as unity in applying the flexure formula.

---

[29] J. A. Newlin and G. W. Trayer, *The influence of the form of a wooden beam on its stiffness and strength, II, Form factors of beams subjected to transverse loading only,* Nat. Advis. Comm. Aero. Tech. Rept. 181, Washington, 1924.

For rectangular cross sections characteristic of structural lumber, the **moment of inertia (I)** $= bd^3/12$, in which b = actual width, inches, and d = actual depth, inches. For rectangular sections c, appearing in the flexure formula, is one-half actual depth of beam.

Calculation of **maximum bending moment (M)** induced by a load is determined by the size of the load and its position on the beam. In the case of a simple beam, uniformly loaded throughout its length, maximum moment (M) is induced at the midpoint of length, as may be seen by inspection of the moment diagram (Fig. 13), and $M = Wl/8$ in which W = total uniformly distributed load, pounds, and l = span, inches. Substituting in the flexure formula, gives

$$\frac{Wl}{8} = \frac{fI}{c} \tag{12}$$

Example 1. What maximum uniformly distributed net load can be supported by a surfaced 3-by-8-inch beam of Select Structural Douglas fir (Coast region) joist and plank over a 20-foot span without exceeding allowable fiber stress in bending?

$$f \text{ (from Table 24)} = 1900 \text{ pounds per square inch}$$

Transposing equation 12 gives

$$W = \frac{8 \times 1900 \times I}{(12 \times 20) \times c}$$

in which $$\frac{I}{c} = \frac{bd^2}{6} = \frac{2\frac{5}{8} \times (7\frac{1}{2})^2}{6} = 24.61 \text{ inches}^3$$

and $$W = \frac{8 \times 1900 \times 24.61}{240} = 1559 \text{ pounds}$$

The weight of the beam must be subtracted from the calculated value for W to arrive at the net distributed load (W_n) carried by the beam.

Consideration of the moment diagram (Fig. 12) for a concentrated load at midspan of the same beam, comparing the two equivalent expressions for moment (M), shows immediately that a concentrated load (P) only one half as large as the net uniformly distributed load (W_n) could be applied:

$$\text{Maximum moment } (M) = \frac{Pl}{4} = \frac{W_n l}{8} \quad \text{or} \quad P = \frac{W_n}{2}$$

Net load (W_n) is used in this expression comparing different types of load distribution inasmuch as weight of the beam is treated as a uniformly distributed load under any type of load application.

For a beam of given dimensions and known allowable f, the net load that can be carried under any desired combination of concentrated or distributed load may be readily determined from the bending moment (M) as calculated from the flexure formula. Conversely, the **section modulus (I/c),** and thus the dimensions, of a beam of given span and allowable f required to support a known load may be determined by transposing the equation, thus:

$$\frac{I}{c} = \frac{M}{f}$$

Using the same values employed in Example 1, we have

$$\frac{I}{c} = \frac{Wl}{8f} = \frac{1559 \times 240}{8 \times 1900} = 24.61 \text{ inches}^3$$

As shown previously, this is the I/c value corresponding to $bd^2/6$ for a dressed 3-by-8-inch beam. For convenience in design, tables showing the I/c values for all standard sizes of surfaced and rough structural lumber are available in a number of publications.[30]

It has been demonstrated experimentally that a beam of circular cross section can support essentially the same load as a square beam of the same cross-sectional area. Since the moment of inertia of a square section is approximately 118 percent that of a circle of the same area, the basis for inclusion of a form factor in the flexure formula is indicated. In the direct method of calculating bending moments for beams of circular cross section, the flexure formula is used as follows:

---

[30] *Wood structural design data,* Vol. I, Nat. Lbr. Mfrs. Assn., Washington, 1941.

Also *Timber engineers handbook,* edited by H. J. Hansen, John Wiley & Sons, New York, 1948.

$$M = \frac{1.18fI}{c}$$

in which $I = \pi r^4/4$ and c = radius (r).

Similarly, for a square beam loaded diagonally rather than on a flat surface, $M = 1.414fI/c$, in which I is the moment of inertia of the section, and c is one-half the diagonal length of the section.

The successful use of these form factors indicates a supporting effect of the underlying fibers in cross sections of such shape that the highly stressed surface fibers are reinforced by a proportionately larger number of lesser stressed fibers in close proximity to the surface than is the case in rectangular sections loaded normally.

I Beams and Box Beams. Wood beams of I and box section are sometimes employed, particularly in construction where high strength efficiency is desired in a lightweight structure. Aircraft-wing spars are probably the outstanding example of such construction. Theoretically the increased section modulus (I/c) of such a beam should result in a proportionate increase in bending strength in comparison with a rectangular beam of equal weight. The two sections illustrated in Fig. 59 have equal cross-sectional areas of 60 square inches, but the section modulus of the I section, calculated by subtraction of the I value of the "cut-out" areas from that of a 6-by-14-inch rectangle, is more than 1¾ times as great as that of the 6 by 10.

It has been shown,[31] however, that a form factor for modulus of rupture for I and box sections may reduce this apparent increase by a considerable amount. The form factor (F) of such sections may be calculated from the following equation:[32]

$$F = 0.50 + 0.50\left(\frac{K(t_2 - t_1)}{t_2} + \frac{t_1}{t_2}\right) \qquad (13)$$

---

[31] Newlin and Trayer, footnote 29.

[32] *Wood handbook,* rev., U. S. Dept. Agr. Unnumbered Publ., Washington, 1940, p. 154.

in which K is a value dependent on the ratio of the depth of compression flange to depth of the beam, t_1 = thickness of web or combined thickness of two webs as in a box beam, and t_2 = over-all width of beam. In the example cited, $K = 0.230$, and, from equation 13,

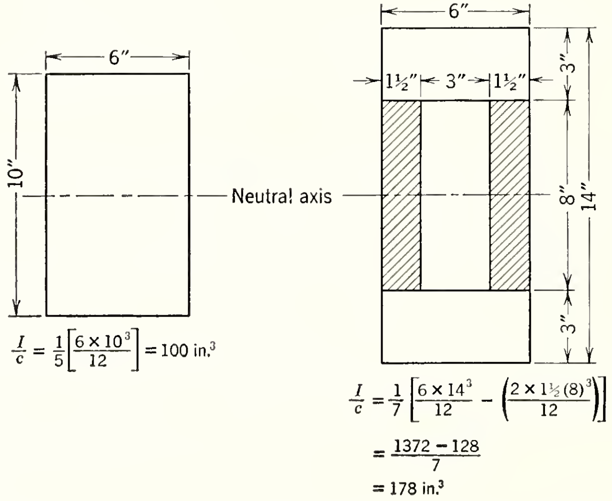

6"
10"
$\frac{I}{c} = \frac{1}{5}\left[\frac{6 \times 10^3}{12}\right] = 100 \text{ in.}^3$
Neutral axis
6"
1½"
3"
1½"
3"
8"
14"
3"
$\frac{I}{c} = \frac{1}{7}\left[\frac{6 \times 14^3}{12} - \left(\frac{2 \times 1\frac{1}{2}(8)^3}{12}\right)\right]$
$= \frac{1372 - 128}{7}$
$= 178 \text{ in.}^3$

FIG. 59. Comparative section-modulus values for rectangular and I sections of equal area.

$$F = 0.50 + 0.50\left(0.230\,\frac{(6-3)}{6} + \frac{3}{6}\right)$$

$$= 0.50 + 0.50\ (0.115 + 0.50)$$

$$= 0.50 + 0.3075 = 0.8075$$

Calculation of bending moment for both beams by means of the flexure formula (equation 11) on the assumption that a modulus-of-rupture value of 7500 pounds per square inch is applicable, shows

$$M = 7500 \times 100 = 750{,}000 \text{ pound-inches}$$

for the 6-by-10 rectangular beam, and

$$M = 0.8075 \times 7500 \times 178 = 1{,}075{,}000 \text{ pound-inches}$$

for the I beam. This particular I beam is thus seen to be slightly less than 1½ times as strong as the rectangular beam of equal weight.

Laminated Beams. One of the advantages of laminated-wood beams is the possibility of utilizing material of higher grade, or of a stronger species, in those portions of a beam that are subjected to maximum stress, permitting weaker material to be utilized in the remainder of the member. Methods for the design of beams composed of two types of material give consideration to the respective fiber-stress and modulus-of-elasticity values of the two materials. In order to assure that the bending strength of a composite beam will be governed by the strength of the stronger face material used in the zone of higher stress, the ratio of core thickness to total depth of beam should not exceed the limits indicated by the following relationship:[33]

$$\frac{d_c}{d_f} = \frac{f_c\, E_f}{f_f\, E_c} \tag{14}$$

in which

d_c = distance from neutral plane to outer fiber of core material, inches
d_f = distance from neutral plane to outer fiber of face material, inches
f_c = allowable fiber stress of core material, pounds per square inch
f_f = allowable fiber stress of face material, pounds per square inch
E_c = modulus of elasticity of core material, pounds per square inch
E_f = modulus of elasticity of face material, pounds per square inch

If the beam is composed of two grades of the same species, differing in fiber-stress value but with the same value for modulus of elasticity, this equation may be simplified to

$$\frac{d_c}{d_f} = \frac{f_c}{f_f}$$

and, if the core is held to a depth within the limit indicated, the strength of the beam may be evaluated from the bending moment as calculated by a special form of the flexure formula (see equation 11):

---

[33] F. F. Wangaard and N. V. Poletika, *Laminated Connecticut red oak,* Northeastern Wood Utiliz. Coun. Bul. 22, 1948, pp. 21–36.

Also A. G. H. Dietz, *Two-species laminated beams,* American Soc. Mech. Eng. Paper 48-WDI-6, Oct. 1948.

$$M = \frac{f_f I}{c}$$

A rectangular beam composed of two species differing in modulus-of-elasticity as well as in fiber-stress value is analogous to an I beam.[34] The faces of higher modulus of elasticity are considered as the flanges of the I beam and the core material as the web, as indicated in Fig. 60. The ratio of flange width (b) to web width (w) is defined by the ratio E_f/E_c, and the moment of inertia (I) of the section may be computed as follows:

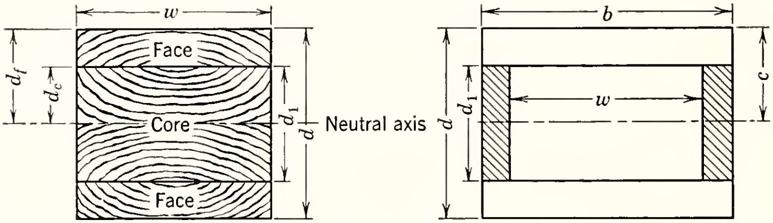


Fig. 60. Cross-sectional dimensions of a two-species laminated beam and analogous I section.

$$I = \left[\frac{bd^3}{12} - \frac{(b - w)d_1{}^3}{12}\right]\frac{E_c}{E_f} \tag{15}$$

in which the significance of dimensions is indicated in Fig. 60. Bending moment is calculated by substituting this value for I in the flexure formula, $M = f_f I/c$. It is not known at present whether this relationship can be improved through the introduction of a form factor, but experiment has shown that actual bending moments can be closely approximated by the method described.

The following example illustrates application of this equation.

---

[34] H. B. McKean, *Mechanical properties and design procedure for glued laminated beams composed of two wood species,* Univ. Mich. School For. and Cons. Bul. 11, 1944.

Also see footnote 33.

Example 2. Determine the maximum bending moment of a laminated beam composed of oak faces and eastern hemlock core meeting the following description:

Width: 5 inches
Depth: 10 inches
Face lamination thickness: 1½ inches
Total thickness of core laminations: 7 inches
E_f: 1,500,000 pounds per square inch
E_c: 1,100,000 pounds per square inch
f_f: 2150 pounds per square inch
f_c: 1100 pounds per square inch

The relation $\frac{d_c}{d_f} = \frac{1100 \times 1{,}500{,}000}{2150 \times 1{,}100{,}000} = 0.70$ (from equation 14) is first tested to determine that stresses in the core do not govern maximum moment, and the calculation is satisfactory, since it shows that face and core will simultaneously reach maximum allowable stress. The design methods illustrated would be unchanged, had any face thickness greater than 1½ inches been selected, but would not be applicable, had a greater proportionate thickness of core material been employed.

From the ratio $E_f/E_c = 1{,}500{,}000/1{,}100{,}000 = 1.36$, the transformed width (b) of the flanges becomes $5 \times 1.36 = 6.8$ inches.

$$\text{The moment of inertia } (I) = \frac{6.8 \times 10^3}{12} - \left(\frac{1.8 \times 7^3}{12}\right)$$

$$= 566 - 51.5 = 514.5 \text{ inches}^4$$

which for the purpose of calculating bending moment based on allowable fiber stress in the face lamination must be modified by the ratio E_c/E_f, thus:

$$514.5 \times \frac{1.1}{1.5} = 377 \text{ inches}^4$$

By substitution in the flexure formula (equation 11), we get

$$M = \frac{2150 \times 377}{5} = 162{,}000 \text{ pound-inches}$$

(Such a beam 12 feet long, simply supported at the ends, would carry safely a uniformly distributed load of $W = \frac{8M}{l} = \frac{8 \times 162{,}000}{144} =$ 9000 pounds.)

Horizontal-Shearing Stress

Horizontal shearing stress (H) in wood beams is ordinarily calculated by the equation

$$H = \frac{VQ}{It} \tag{4}$$

in which

V = vertical shear (end reaction), pounds
Q = statical moment of the area above or below the neutral axis about that axis, inches^3 (Statical moment is the product of the area as defined and the vertical distance from the center of gravity of this area to the neutral axis)
I = moment of inertia of the section, inches^4
t = width of beam at the neutral axis, inches

For the usual rectangular beam of width b and depth d, this equation reduces to

$$H = \frac{3V}{2bd} \tag{16}$$

In the Select Structural Douglas fir (Coast region) joist previously cited (Example 1, page 255) the uniformly distributed load of 1559 pounds limited by fiber stress must be checked to determine whether shearing stresses are within allowable limits for the grade, 120 pounds per square inch. Substituting in equation 16 yields

$$H = \frac{3 \times \frac{1559}{2}}{2 \times 2\frac{5}{8} \times 7\frac{1}{2}} = 60 \text{ pounds per square inch}$$

The shearing stress developed under the allowable load for fiber stress, is in this case, well within allowable limits.

Shearing stresses calculated by the method just described are an approximation, and actual shearing stresses are less than those calculated by this method when checks are present near the neutral plane at the end of a beam.[35]

---

[35] J. A. Newlin, G. E. Heck, and H. W. March, New method for calculating horizontal shear in wooden beams, *Eng. News-Record,* New York, Vol. 110, 1933, pp. 594–6.

The Forest Products Laboratory[36] and National Lumber Manufacturers Association[37] recommend that in calculating the reaction (V) for use in the formula (1) consideration be given to any relief to the beam resulting from the distribution of load to adjacent parallel beams by flooring or other members of the construction, (2) all loads within a distance equal to the depth of beam from both supports be neglected, and (3) moving loads, if present, be placed so that the largest moving load is situated at three times the depth of beam from the support. If by this procedure, which under certain conditions is still conservative, a timber still fails to meet shear requirements, the reactions should be calculated by recommended methods which are beyond the scope of this discussion.[38]

I Beams and Box Beams. Horizontal shear in I and box beams is calculated by direct application of equation 4.

Laminated Beams. In laminated beams composed of two species, allowable horizontal shearing stress in the weaker core may limit the strength of the member. In computing shearing stress in such a beam, the section is considered as analogous to that of an I beam, and values for **statical moment (Q)**, moment of inertia (I) of the I section, and actual width (b) of the beam at the neutral axis are substituted in equation 4.

As an illustration of the method, the laminated beam described in Example 2 (page 261) that was found to support a total of 9000 pounds has an end reaction (V) of 4500 pounds. The moment of inertia (I) was previously shown to be 514.5 inches^4 (although subsequently modified for direct substitution in the flexure formula), and width (b) of 5 inches is t in the shear equation. The statical moment (Q) is calculated from the dimensions shown in Fig. 61 as follows:

$$\begin{aligned}(6.8 \times 1.5) \times 4.25 + (5 \times 3.5) \times 1.75 &= 43.4 + 30.6 \\ &= 74.0 \text{ inches}^3\end{aligned}$$

$$\text{Area of I section flange} \times \begin{matrix}\text{distance}\\ \text{from center}\\ \text{of gravity to}\\ \text{neutral axis}\end{matrix} + \begin{matrix}\text{area of I}\\ \text{section web}\end{matrix} \times \begin{matrix}\text{distance from}\\ \text{center of}\\ \text{gravity to}\\ \text{neutral axis}\end{matrix} = \begin{matrix}\text{statical}\\ \text{moment } (Q)\end{matrix}$$

---

[36] *Wood handbook,* footnote 32, pp. 150–1.

[37] *Wood structural design data,* footnote 30, p. 50.

[38] *National design specification for stress-grade lumber and its fastenings,* rev., footnote 7, par. 400-D-2.

Substituting these values in the shear equation 4 gives

$$H = \frac{4500 \times 74.0}{514.5 \times 5} = 130 \text{ pounds per square inch}$$

Allowable stress in horizontal shear for laminated structural members should not exceed the limits specified in Table 25 which are applicable to all grades of a species (with the exceptions for density as noted).[39] In this example, permissible working stress in shear for eastern hemlock is 110 pounds per square inch, and shear thus governs the maximum load that may be safely supported. The 9000-pound load calculated on the basis of fiber stress must be reduced by the ratio (110/130) = 0.85, and 9000 × 0.85 = 7650 pounds, the maximum safe uniformly distributed load for this particular beam.

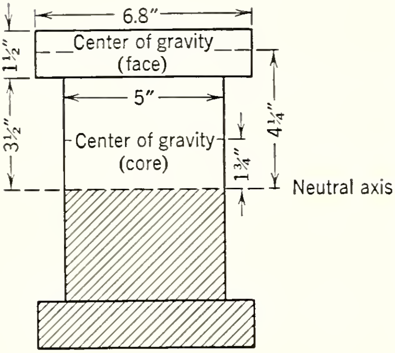


FIG. 61. Critical dimensions required for calculation of horizontal shear in a two-species laminated beam.

DEFLECTION

The basic equation governing the deflection of a beam is

$$\frac{\delta^2 y}{\delta x^2} = \frac{M}{EI} \tag{17}$$

in which $\delta^2 y/\delta x^2$ is the second derivative of deflection (y) with respect to distance (x) from support of a beam, M = bending moment at the point x, E = modulus of elasticity, and I = moment of inertia of the section.

For a simple beam carrying a concentrated center load, this equation reduces to

$$y = \frac{Pl^3}{48EI} \tag{18}$$

in which y = maximum deflection at midspan, inches; P = concentrated applied load, pounds; l = length of span, inches; E = modulus of elasticity, pounds per square inch; and I = moment of inertia, inches.[4]

---

[39] *National design specification for stress-grade lumber and its fastenings,* rev., footnote **7**, par. **902-A-4.**

For a simple beam supporting a uniformly distributed load (W), the equation becomes

$$y = \frac{5Wl^3}{384EI} \tag{19}$$

Timber beams under long-time loading acquire a *permanent set* about equal to the original deflection. This is especially true of green timbers that are permitted to season under load, but partially seasoned timbers will also sag to some extent. For this reason it may be desirable in certain instances to make allowance for sag by doubling dead loads and long-time live loads, but not live loads of short duration, in computing the deflection.[40] Under certain conditions immediate deflection due to live loads is more important than the set resulting from long-time loading. In such cases deflection limits have been established for live load alone, and only the immediate deflection caused by live loads is calculated. In determining deflections for floor systems supporting plastered ceilings, for example, dead load is ordinarily ignored. Deflection limitations on beams are usually 1/360 span for construction where a high degree of stiffness is required as in floor joists used in connection with plastered ceilings. In other construction, deflection limits, if applied, commonly range between 1/180 and 1/360 span.

If the entire load of 1559 pounds on the 3-by-8-inch Select Structural Douglas fir joist previously mentioned (Example 1, page 255) is considered as a dead load (and, consequently, this value is doubled), the maximum deflection including sag of the 20-foot joist is calculated from equation 19 as follows:

$$y = \frac{5 \times (1559 \times 2) \times 240^3}{384 \times 1{,}600{,}000 \times 92.4} = 3.8 \text{ inches}$$

If it is assumed that 1/360-span limitations govern in this case, it may be seen that the limit of 240/360, or 0.67 inch, is greatly exceeded. Since deflection is directly proportional to load, it is obvious that the dead load (W), determined in Example 1 on the basis of fiber stress, must be reduced to 0.67/3.8 × 1559, or 274 pounds, in order to meet the deflection limitations imposed.

---

[40] *Wood handbook,* footnote 32, p. 151.

TABLE 25. VALUES USED IN DESIGN OF GLUED-LAMINATED STRUCTURAL MEMBERS*

Species	Compression Parallel to Grain, psi	Horizontal Shear, psi
Ash, white	2200	200
Beech	2400	200
Birch	2400	200
Chestnut	1600	145
Cypress, southern	2200	160
Cypress, tidewater	2200	160
Douglas fir, all regions, dense	2575	170
Douglas fir, coast region, close grained	2350	145
Douglas fir, coast region	2200	145
Douglas fir, inland region, close grained	2225	145
Douglas fir, inland region	2075	145
Elm, rock	2400	200
Elm, soft	1600	160
Gum, black and red	1600	160
Hemlock, eastern	1400	110
Hemlock, west coast	1800	120
Hickory	3000	225
Larch, dense	2575	185
Larch, close grained	2350	160
Larch	2200	160
Maple, hard	2400	200
Oak, red and white	2000	200
Pecan	3000	225
Pine, Norway	1600	135
Pine, southern longleaf	2575	205
Pine, southern, dense	2575	205
Pine, southern	2200	175
Poplar, yellow	1600	130
Redwood, close grained	2125	110
Redwood	2000	110
Spruce, eastern	1600	135
Tupelo	1600	160

* Values for compression parallel to grain contained in this table are not working stresses and are used only as limiting values as discussed in the text.

From *National design specification for stress-grade lumber and its fastenings*, rev., Table 25, Nat. Lbr. Mfrs. Assn., Washington, 1948.

I Beams and Box Beams. In calculating the deflection of beams of I and box section, or other variations from the usual rectangular cross section, no form factors are involved, and the moment of inertia (I) for the section is used in the applicable deflection equation dependent on the type of beam loading.

Laminated Beams. Calculation of the deflection of two-species laminated beams depends on the determination of an apparent modulus of elasticity which is, in turn, dependent on the modulus of elasticity values for the two materials in combination.

The basic equation[41] is

$$E_a = \frac{1}{I} \sum_{i=1}^{i=n} E_i I_i \tag{20}$$

in which

I = moment of inertia of the entire cross section about the neutral axis, inches^4

E_i = modulus of elasticity of the ith lamination, pounds per square inch

I_i = moment of inertia of the ith lamination about the neutral axis of the section, inches^4

E_a = apparent modulus of elasticity of the beam, pounds per square inch

For a two-species combination this equation becomes

$$E_a = \frac{E_f I_f + E_c I_c}{I} \tag{21}$$

in which the subscripts f and c refer to face and core, respectively. Returning to the beam previously cited as Example 2, we find

$$I = \frac{bd^3}{12} = \frac{5 \times 10^3}{12} = 417 \text{ inches}^4$$

in which I is the moment of inertia of the entire section; and

$$I_c = \frac{5 \times 7^3}{12} = 142.7 \text{ inches}^4$$

in which I_c is the moment of inertia of the core laminations. By subtraction, the moment of inertia of the face laminations is

$$I_f = I - I_c = 417 - 142.7 = 274.3 \text{ inches}^4$$

---

[41] Forest Products Laboratory, *Design of wood aircraft structures,* ANC Bul. 18, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1944.

If values are substituted in equation 21, the apparent modulus of elasticity of the entire beam is

$$E_a = \frac{1{,}500{,}000 \times 274.3 + 1{,}100{,}000 \times 142.7}{417}$$

$$= 1{,}360{,}000 \text{ pounds per square inch}$$

Considering the 7650-pound load that met both shear and fiber stress requirements in previous calculations on this beam (Example 2, page 263) as a live load, and calculating immediate deflection by substituting values in equation 19, we get

$$y = \frac{5 \times 7650 \times 144^3}{384 \times 1{,}360{,}000 \times 417} = 0.52 \text{ inch}$$

If a deflection limitation of 1/360 span were to be maintained, the maximum deflection permitted would be 144/360 = 0.40 inch, and the maximum uniformly distributed live load producing an allowable deflection would be 7650 × 0.40/0.52 = 5880 pounds.

Columns

Wood columns are classed as **short, intermediate,** or **long** columns, dependent on the ratio (L/d) of unsupported length to least dimension. The L/d ratio determines the relative importance of strength in compression parallel to grain and modulus of elasticity on the load-carrying capacity of a column.

The strength of a short column, in which unsupported length is less than 11 times the least cross-sectional dimension, depends entirely on the strength of the wood in compression parallel to grain. The load that can be carried by a long column is entirely dependent on the stiffness of the wood. Between these extremes is the intermediate column in which both compressive strength parallel to grain and stiffness are involved.

SHORT COLUMNS

Working stresses in compression parallel to grain (C), presented in Table 24, are directly applicable in computing safe loads for rectangular solid columns meeting the requirements of short columns, that is, with L/d not exceeding 11.

For short columns

$$\frac{P}{A} = C \tag{22}$$

in which P = load, pounds, and A = cross-sectional area, square inches.

Example 3. An 8-by-8-inch, surfaced 4 sides, No. 1 Structural longleaf pine post 6 feet long can support a normal load as follows:

The L/d ratio $= 72/7.5 = 9.6$, and the post is therefore a short column.

$$A = 7\tfrac{1}{2} \times 7\tfrac{1}{2} = 56.2 \text{ square inches}$$

$$C = 1150 \text{ pounds per square inch} \quad \text{(from Table 24)}$$

Transposing equation 22 gives

$$P = 56.2 \times 1150 = 64{,}600 \text{ pounds}$$

INTERMEDIATE COLUMNS

Intermediate columns are those in which the L/d ratio may vary from 11 to that at which the allowable stress per unit area is two-thirds that of a short column of the same material. As its slenderness increases within this range, the capacity of a column for supporting loads becomes increasingly dependent on modulus of elasticity and less dependent on the compressive strength of the wood.

The maximum L/d ratio of an intermediate column corresponding to a column with a load-carrying capacity two-thirds that of a short column, is equivalent to K, the value for which is determined from the relationship:[42]

$$K = \frac{\pi}{2}\sqrt{\frac{E}{5C}} \quad \text{or} \quad 0.702\sqrt{\frac{E}{C}} \tag{23}$$

Calculation of safe loads for intermediate columns is carried out by using the Forest Products Laboratory parabolic formula:[43]

---

[42] *National design specification for stress-grade lumber and its fastenings,* rev., footnote 7.

$$\frac{P}{A} = C\left[1 - \frac{1}{3}\left(\frac{L}{Kd}\right)^4\right] \tag{24}$$

in which K is the value derived in equation 23. In the parabolic formula, C is working stress in compression parallel to grain from Table 24, but it is evident that, in effect, the allowable stress per unit area is progressively scaled down from C at L/d of 11 to a value of $\frac{2}{3}C$ for a column with L/d ratio equal to K.

Example 4. Calculate the safe load of normal duration that can be carried by an 8-by-8-inch, surfaced 4 sides, No. 1 Structural longleaf pine column with a 12-foot unsupported length.

C = 1150 pounds per square inch (from Table 24)

E = 1,600,000 pounds per square inch (from Table 24)

$$\frac{L}{d} = \frac{12 \times 12}{7\frac{1}{2}} = 19.2$$

For this grade of longleaf pine (from equation 23),

$$K = 0.702\sqrt{\frac{1{,}600{,}000}{1150}} = 26.2$$

Since L/d lies between 11 and 26.2, this is an intermediate column. By substitution of values in equation 24,

$$\frac{P}{56.2} = 1150\left[1 - \frac{1}{3}\left(\frac{19.2}{26.2}\right)^4\right]$$

$$= 1150\left(1 - \frac{0.288}{3}\right) = 1150\ (0.904) = 1040$$

and $$P = 56.2 \times 1040 = 58{,}500 \text{ pounds}$$

LONG COLUMNS

Columns with an L/d ratio greater than K are dependent for their load-carrying capacity entirely on the stiffness of the wood, and ultimate failure occurs as a result of lateral buckling. Since a constant value of modulus of elasticity is assigned to a species regardless of grade, the same stresses are permitted for all grades of a given species.

---

[43] J. A. Newlin and J. M. Gahagan, *Tests of large timber columns and presentation of the Forest Products Laboratory column formula,* U. S. Dept. Agr. Tech. Bul. 167, Washington, 1930.

Safe loads for long columns are calculated by a form of the Euler equation:

$$\frac{P}{A} = \frac{0.329E}{\left(\frac{L}{d}\right)^2} \tag{25}$$

in which E = modulus of elasticity, pounds per square inch, from Table 24 and L/d = ratio of length to least dimension. A reduction factor of 2.5, slightly less than that formerly advocated, has been included in this equation to account for variability and possible overloading.[44]

Example 5. Determine the maximum safe load of normal duration that can be carried by an 8-by-8-inch, surfaced 4 sides, No. 1 Structural longleaf pine column with a 20-foot unsupported length.

$$C = 1150 \text{ pounds per square inch} \quad \text{(from Table 24)}$$

$$E = 1{,}600{,}000 \text{ pounds per square inch} \quad \text{(from Table 24)}$$

$$\frac{L}{d} = \frac{20 \times 12}{7\frac{1}{2}} = 32$$

Since K, from Example 4, = 26.2, this is a long column, and load is calculated by the Euler formula (equation 25).

$$\frac{P}{A} = \frac{0.329 \times 1{,}600{,}000}{(32)^2} = 514 \text{ pounds per square inch}$$

and $P = 56.2 \times 514 = 28{,}800$ pounds

The maximum L/d ratio recommended in the design of solid columns is 50. The general relationship between allowable stress per unit area (P/A) and L/d ratio for all three types of column is indicated in Fig. 62.

---

[44] "It has been maintained that since the fiber stress at proportional limit is never passed in going to the maximum load of long columns the factor of safety could be about one-half that for short columns. The modulus of elasticity of timber is its most variable property and the one most difficult to estimate visually. Tests of clear wood and the laws of probability indicate that one timber in 100 will have less than 56 percent of the average stiffness. It is believed, therefore, that a factor of safety of 3 should be used for long columns."—*Recommended Building Code Requirements,* footnote 1.

The strength of a round column or post may be considered the same as that of a square column of the same cross-sectional area. A long tapered round column may be assumed to support a load identical with that of a square column of the same length and cross-sectional area. The diameter of a tapered column, for the purpose of computing cross-sectional area, is taken as the sum of the minimum diameter and ⅓ the difference between minimum and maximum diameters, as long as the resultant diameter is not greater than 1½ times the diameter at the small end. In any case, the induced compressive stress per unit area (P/A) at the small end of a tapered column must not exceed that allowed for a short column.

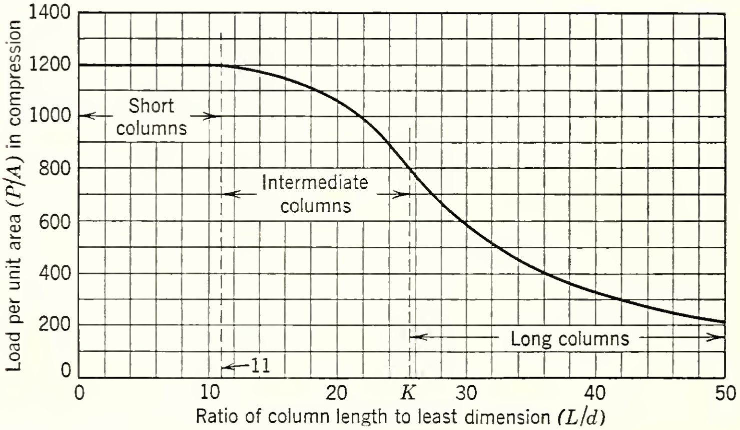


FIG. 62. Relationship of allowable stress per unit area to L/d for solid wood columns.

LAMINATED CONSTRUCTION

Glue-laminated columns are designed as long, intermediate, or short columns on the general basis described for structural lumber. However, working stresses in compression parallel to grain are increased when seasoned joist and plank grades, or seasoned boards graded as joist and plank, are used in the fabrication of the laminated member. In the National Design

Specification, allowable stress in compression parallel to grain for laminated columns is increased by 50 percent over that given in Table 24, but not to exceed 90 percent of the value shown in Table 25.

Tension Parallel to Grain

Working stresses in tension parallel to grain, required for design of members stressed in direct tension, are taken as equivalent to the values for f, extreme fiber stress in bending, shown in Table 24. In actual test this assumption has been shown to represent conservative practice. In grading joist and plank for such use, the sum of the sizes of knots in any 6 inches of length is limited to twice the maximum permissible size of knot, and two knots of maximum size should not be located in the same 6 inches of length of any face.

Combined Bending and Axial Loads

A wood member subjected to **combined bending and axial loads in tension or compression,** such as a truss-chord member carrying a load inducing a bending stress, must be sufficiently large to withstand the additive effect of such loads calculated as though they were applied separately.

A member loaded in flexure and axial tension is proportioned so that

$$\frac{P/A}{t} + \frac{M/S}{f} \text{ is not greater than } 1 \qquad (26)$$

In this equation,[45]

P/A = axial tension load per unit area of cross section, pounds per square inch

M = maximum bending moment, pound-inches

S = section modulus I/c, inches^3

Therefore,

$M/S = Mc/I$ = fiber stress in bending, pounds per square inch

---

[45] *National design specification for stress-grade lumber and its fastenings*, rev., footnote 7, par. 403.

t = working stress in tension parallel to grain, pounds per square inch (f in Table 24)

f = working stress in extreme fiber in bending, pounds per square inch (Table 24) if a flexural load only is assumed

Since $t = f$, the limitations of equation 26 are equivalent to keeping the sum of the stress in direct tension and fiber stress in bending within the working stress f.

Similarly, a member subjected to **combined bending and axial compression loads** is proportioned so that

$$\frac{P/A}{c} + \frac{M/S}{f} \text{ is not greater than } 1 \tag{27}$$

In this equation, P/A = axial compression load per unit area of cross section, pounds per square inch, and c = allowable stress in compression parallel to grain, pounds per square inch, for the L/d ratio of the column, assuming a compression load only (Table 24 value for C reduced according to the appropriate column formula).

Example 6. A short column, surfaced 4 sides, of nominal 6-by-10 dimensions, subjected to an axial compression load of 7000 pounds and a lateral load on the narrow face inducing a bending moment of 150,000 pound-inches, with a working stress in compression parallel to grain of 1600 pounds per square inch and working stress in extreme fiber in bending of 2000 pounds per square inch, would be examined according to the relationship:

$$\frac{\dfrac{7000}{5\frac{1}{2} \times 9\frac{1}{2}}}{1600} + \frac{\dfrac{150{,}000}{\dfrac{5\frac{1}{2} \times (9\frac{1}{2})^2}{6}}}{2000} = \frac{134}{1600} + \frac{1814}{2000} = 0.084 + 0.907 = 0.991$$

The member is seen to be loaded to 8.4 percent of its capacity in compression alone, to 90.7 percent of its capacity in bending alone, and to 99.1 percent of its capacity in combined stress.

Compression at an Angle to Grain

Allowable stress in compression acting at an angle to the grain intermediate to 0 and 90 degrees is computed by the Hankinson formula.[46]

$$N = \frac{P\,Q}{P \sin^2 \theta + Q \cos^2 \theta} \tag{28}$$

in which N = allowable stress induced by a compression load acting at an angle θ to the grain direction, pounds per square inch

P = allowable stress in compression parallel to grain, pounds per square inch (C in Table 24)

Q = allowable stress in compression perpendicular to grain, pounds per square inch (Table 24)

θ = angle between direction of load and direction of grain

Shearing Stress in Joint Details[47]

Allowable stresses for shear in joint details may be increased 50 percent over those presented for horizontal shear in Table 24.

REFERENCES

AMERICAN ASSOCIATION OF STATE HIGHWAY OFFICIALS: *Standard specifications for highway bridges,* Washington, 1941.

AMERICAN RAILWAY ENGINEERS ASSOCIATION: Notes on working stresses for structural grades of American Lumber Standards. *Manual Am. Ry. Eng. Assn.,* Chicago, Ed. of 1929, pp. 536–43.

AMERICAN SOCIETY FOR TESTING MATERIALS: Standard specifications for structural wood joist and plank, beams and stringers, and posts and timbers. Serial Designation: D245-37, 1937 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

———: Definitions of terms relating to timber. Serial Designation: D9-30, 1930 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

BETTS, HAROLD S.: *Timber—its strength, seasoning, and grading.* McGraw-Hill Book Co., New York, 1919.

BUREAU OF STANDARDS: *Lumber. Simplified practice recommendation R16-39.* U. S. Dept. Comm., Washington, 1940.

CLINE, McGARVEY and A. L. HEIM: *Tests of structural timbers.* U. S. Dept. Agr. For. Serv. Bul. 108, Washington, 1912.

[46] *Wood handbook,* footnote 32, p. 56. Also *Investigation of crushing strength of spruce at varying angles of grain,* U. S. Air Serv. Inform. Circ. 259, 1921.

[47] *National design specification for stress-grade lumber and its fastenings,* rev., footnote 7.

Forest Products Laboratory: *Wood handbook,* rev. U. S. Dept. Agr. Unnumbered Publ., Washington, 1940.

———: *Design of wood aircraft structures.* ANC Bul. 18. Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1944.

Forsaith, C. C.: *The technology of New York State timbers.* N. Y. State Coll. For. Tech. Publ. 18, Syracuse, 1926.

Hansen, Howard J.: *Timber engineers handbook.* John Wiley & Sons, New York, 1948.

———: *Modern timber design.* 2d. ed. John Wiley & Sons, New York, 1948.

Holtman, Dudley F.: *Wood construction—principles, practice, details.* McGraw-Hill Book Co., New York, 1929.

Jacoby, Henry S., and Roland P. Davis: *Timber design and construction* 2d ed. John Wiley & Sons, New York, 1930.

Koehler, Arthur: *The properties and uses of wood.* McGraw-Hill Book Co., New York, 1924.

Markwardt, L. J.: *Comparative strength properties of woods grown in the United States.* U. S. Dept. Agr. Tech. Bul. 158, Washington, 1930.

———: Wood as an engineering material (Eighteenth Edgar Marburg lecture). *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 43, 1943, pp. 435–92.

——— and T. R. C. Wilson: *Strength and related properties of woods grown in the United States.* U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935.

McElhanney, T. A. and associates: *Canadian woods: their properties and uses.* Canada Dept. Int., Ottawa, 1935.

National Lumber Manufacturers Association: *Wood structural design data, Vol. I.* Washington, 1941.

———: *National design specification for stress-grade lumber and its fastenings,* rev. Washington, 1948.

Newlin, J. A.: Unit stresses in timber. *Proc. Am. Soc. Civil Eng.,* New York, Vol. 52, Sept. 1926, pp. 1436–43. Also in *Trans. Am. Soc. Civil Eng.,* New York, Vol. 91, Dec. 1927, pp. 400–07.

——— and J. M. Gahagan: *Tests of large timber columns and presentation of the Forest Products Laboratory column formula.* U. S. Dept. Agr. Tech. Bul. 167, Washington, 1930.

——— and R. P. A. Johnson: *Basic grading rules and working stresses for structural timbers.* U. S. Dept. Agr. Dept. Circ. 295, Washington, 1923.

——— and ———: Structural timbers—defects and their influence on strength. *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 24, Pt. 2, 1924, pp. 975–87.

——— and Trayer, G. W.: *The influence of the form of a wooden beam on its stiffness and strength, II. Form factors of beams subjected to transverse loading only.* Nat. Adv. Comm. Aero. Tech. Rept. 181, Washington, 1924.

——— and T. R. C. Wilson: *Mechanical properties of woods grown in the United States.* U. S. Dept. Agr. Bul. 556, Washington, 1917.

Parker, Harry: *Simplified design of structural timber.* John Wiley & Sons, New York, 1948.

RECORD, SAMUEL J.: *The mechanical properties of wood.* John Wiley & Sons, New York, 1914.

U. S. DEPT. OF COMMERCE: *Recommended building code requirements for working stresses in building materials.* U. S. Dept. Comm. Bldg. Code Com. Rept., Washington, 1926.

WEST COAST LUMBERMEN'S ASSOCIATION: *Douglas fir use book,* Seattle, 1942.

WILSON, T. R. C.: *Guide to the grading of structural timbers and the determination of working stresses.* U. S. Dept. Agr. Misc. Publ. 185, Washington, 1934. Also Supplement 1, For. Prod. Lab. Rept. R1225 (1940) and Supplement 2, For. Prod. Lab. Rept. R1715 (1948).

———: *The glued laminated wooden arch.* U. S. Dept. Agr. Tech. Bul. 691, Washington, 1939.

PART 4

Timber Testing[1]

WORKING PLAN

Before making a series of timber tests on a given project it is practically essential to prepare a working plan as a guide to the investigation. This should include a discussion of: (1) the purpose of the tests to be made; (2) the kind, size, condition, and amount of material needed; (3) the method of collection and disposition of material, including a full description of the system of marking; (4) the test procedure, with details of any special apparatus and methods used; and (5) the proposed method of analyzing the data obtained and the nature of the final report. Great care should be taken in the preparation of this plan in order that all problems arising may be anticipated as far as possible and delays and unnecessary work avoided. A comprehensive study of previous investigations along the same or related lines should prove very helpful in outlining the work and preparing the report. A sample working plan is presented on pages 353–67.

FORMS OF MATERIAL TESTED

In general, four forms of material are tested, namely: (1) small clear pieces, usually 2 by 2 inches in cross section or smaller, depending on kind of test; (2) timbers in structural sizes, such as bridge stringers, joists, car sills, and columns; (3) built-up structural forms and fastenings, such as built-up beams, trusses, and various kinds of joints;[2] and (4) manufactured articles or products such as ladders, tool handles, shafts, wagon tongues, crossarms, insulator pins, poles, containers, and various forms of plywood or laminated-wood construction.

---

[1] The methods of timber testing described in the following pages are, for the most part, those used by the Forest Products Laboratory, U. S. Forest Service, and conform to the standard methods adopted by the American Society for Testing Materials.

See Standard methods of testing small clear specimens of timber, Serial Designation: D143-48, 1948 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

Also Standard methods of conducting static tests of timbers in structural sizes, Serial Designation: D198-27, 1927 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

Standard methods for testing plywood, veneer, and other wood and wood-base materials, Serial Designation: D805-47, 1947 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

SIZE OF SPECIMENS IN RELATION TO PURPOSES OF TEST

The size of the test specimen must be governed largely by the purpose for which the test is made, although the size of the available material, the limitations of treatment, and other factors must often be taken into consideration. If the effect of a single factor, such as uniformly distributed moisture, is the object of experiment, it is necessary to use small pieces of wood in order to eliminate as far as possible all disturbing factors. If the specimens are too large, it is impossible to secure enough perfect pieces from one tree to form a series for various tests. Moreover, the drying process with large timbers is very difficult and irregular and requires a long period of time, besides causing checks and internal stresses which may obscure the results obtained.

On the other hand, the smaller the dimensions of the test specimen, the greater becomes the relative effect of the inherent factors affecting the mechanical properties. For example, the effect of a knot of given size is more serious in a small stick than in a large one. Moreover, the smaller the specimen the fewer growth rings it contains; hence, there is greater opportunity for variation due to minor irregularities of grain.

Small clear specimens of timber are tested principally in static bending, compression parallel to the grain, impact bending, compression perpendicular to the grain, hardness, shear parallel to the grain,[3] tension perpendicular to the grain, cleavage, and tension parallel to the grain. Such tests are essential in obtaining: (1) data for comparing the mechanical properties of various species; (2) data for the establishment of correct strength functions which, in conjunction with results of tests of timbers in structural sizes, afford the basis for fixing allowable stresses; and (3) data on which to determine the influence on the mechanical properties of such factors as density, locality of growth, position in cross section of trunk, height of timber in the tree, change of properties with seasoning, and change from sapwood to heartwood.

---

[2] For procedure in testing fabricated beams, and the like, consult: Standard methods of conducting static tests of timbers in structural sizes, footnote 1.

[3] The test for shearing strength perpendicular to the grain is not included as one of the principal tests, since in such a test the strength is limited by the shearing resistance parallel to the grain.

Tests on timbers in structural sizes are made to afford: (1) data on which to base the formulation of grading rules and specifications; (2) data on which to establish the relation between the strength properties of structural timbers and of small clear specimens cut from them, and for use in the establishment of allowable stresses; (3) data on the influence of defects on the mechanical properties of timbers; (4) data on the strength properties of different species in structural sizes; (5) data for use in checking existing formulas relating to structural timbers; (6) data on the influence of seasoning on the mechanical properties; (7) data on the effect of form and shape of specimen on the properties; and (8) data on the influence of preservatives and methods of preservative treatment on the mechanical properties. The tests made on such timbers are classified as major and minor tests. The former comprise (*a*) static bending tests on the entire timbers under investigation, and (*b*) tests in compression perpendicular to the grain and compression parallel to the grain on sizable pieces cut from the principal members; in all cases the specimens contain such defects as are normal to the material under test. The minor tests are those in static bending, compression parallel to the grain, compression perpendicular to the grain, hardness, and shear parallel to the grain, which are made on small clear specimens cut from the structural timbers.

MOISTURE DETERMINATION

Since the amount of moisture contained in wood has an important bearing on its strength (see Moisture Content, page 179), it is essential that the moisture content of all specimens be determined at the time of testing and definitely stated with the derived strength values. Lack of such data renders the results of any test practically valueless for comparative purposes.

Standard tests are made on specimens in the unseasoned condition and also on matched specimens of air-dry material. The former tests are considered preferable for many purposes, since the unseasoned material is well above the fiber-saturation point, below which changes in moisture content are accompanied by differences in strength; consequently, variations in moisture content, even over wide limits, do not necessitate any final adjustment of results. In air-dry material, on the other hand, even slight variations in moisture may have an appreciable effect on the derived strength values, and in order to make comparisons it is necessary to adjust the results to a definite moisture content, which is usually taken as 12 percent.[4]

The average moisture content of test specimens is determined immediately after testing from small sections cut near the failure.[5] In timbers in structural sizes it is desirable to know not only the average moisture content of the specimen near the point of failure, but also its distribution through the cross section of the material at that point. To this end, a second section, 1 inch in thickness, is taken and cut up so as to obtain an outside, a middle, and an inner portion of approximately equal areas. Separate moisture determinations are made for each of these three portions.

The procedure in determining the moisture content of the selected sections is as follows:

1. Immediately after obtaining the moisture samples, all loose splinters are removed and the weights of the sections determined to an accuracy of 0.2 percent or better.
2. The material is open-piled in an oven and dried at a temperature of 100°C. (212°F.) until constant weight is obtained.
3. The samples are again carefully weighed in this oven-dry condition.
4. The loss in weight expressed in percent of the oven-dry weight is considered to be the moisture content of the specimens from which the respective samples were obtained.

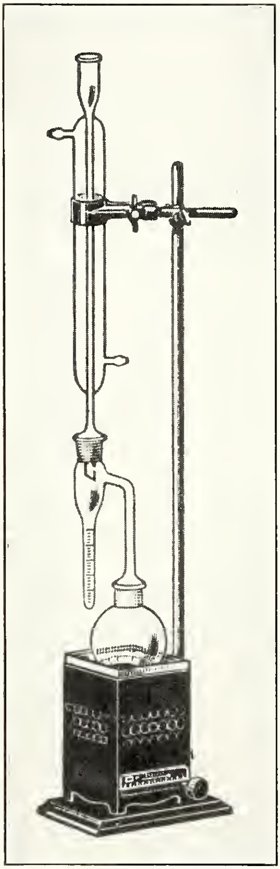
A more accurate method for determining moisture content of woods that contain volatile oils or resins is known as the *distil-*

---

[4] See equation 10, page 186, for method of adjustment of strength properties with changes in moisture content below fiber saturation.

[5] See ensuing description of various tests for nature of moisture sections used.

lation method.[6] A weighed sample of wood chips or sawdust is immersed in xylol in a flask provided with a reflux condenser and a connecting trap (Fig. 63). When the flask is heated, moisture from the wood, xylol, and oils are volatilized together and condensed in the reflux condenser. Condensed water is collected in the graduated trap and its volume measured directly (usually in cubic centimeters) while the xylol and oily extractives are returned to the flask. Distillation is continued until no additional water collects in the trap. Moisture content is then calculated as weight of water collected, and expressed as a percentage of dry weight, that is, original weight less the weight of moisture removed.



Forest Products Laboratory Photo

Fig. 63. Apparatus for determining moisture content by the distillation method.

In determining the moisture content of wood that has received an oil-preservative treatment, oven-dry weight of oil-free wood is determined by extracting the preservative with a suitable solvent, following the distillation process just described, and oven-drying the extracted sample to constant weight at 105°C. (221°F.).

MACHINES FOR STATIC TESTS

The standard universal machines used for tests of other structural materials are also used for wood. These may be of the hydraulic or of the screw type. By suitable control valves, gear ratios, or motor speeds, either type of machine may impose a uniform rate of strain on a test specimen.

---

[6] Standard method of test for water in petroleum products and other bituminous materials, Serial Designation: D95-46, 1946 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

Also John M. McMillen, *Methods of determining the moisture content of wood,* For. Prod. Lab. Rept. R1649, Madison, 1947.

The standard universal machines for static tests can be used for transverse bending, compression, tension, shear, hardness, and cleavage. Special machines are required for impact bending and toughness tests (see Figs. 72 and 88). A universal machine for static tests consists of two main parts, namely: (1) the straining mechanism, and (2) the weighing apparatus.

The straining mechanism itself consists of two parts, a crosshead and a platform, one of which is driven mechanically or hydraulically.

In one type of mechanical machine the movable crosshead is operated by a number of upright steel straining screws that pass through openings in the platform and bear upward on the bed of the machine. In some machines the lower ends of these screws have geared nuts all rotated simultaneously by a system of gears which cause the movable crosshead to rise and fall as desired; in others the screws themselves are made to rotate.

The weighing platform of a mechanical-type testing machine rests on knife edges carried by primary levers of the weighing apparatus, the fulcrum being on the bed of the machine. In older models any pressure on this platform is directly transmitted through a series of levers to the weighing beam. This beam is balanced before test by means of an adjustable counterpoise. In operation the beam is kept in balance by means of another poise, moved by a screw that is operated manually or automatically. The larger units of load are read from the graduations along the side of the beam, while the intermediate smaller weights are observed on the dial at the end of the beam. More recently, the load on the weighing platform is reduced through a series of levers and transmitted to a calibrated pendulum. The linear displacement of the pendulum is translated into the rotary movement of a dial pointer, and the load is read directly on the dial scale.

The machine is driven by power from a shaft or a motor and is so geared that various speeds are obtainable. In making tests the operation of the straining screws is always downward so as to bring pressure to bear on the weighing platform. For tests in tension and cleavage the specimen is attached to the movable crosshead and to a steel cage, above this crosshead, that rests directly on the weighing platform. A tension load is thus developed through the downward movement of the lower crosshead. For tests in bending, compression, hardness, and shear the specimen is placed between the movable head and the platform, and a direct compression load applied.

In a common type of hydraulic-testing machine (Fig. 74), the platform or platen is mounted directly on a hydraulic ram and is raised by fluid pumped into the cylinder at a controlled rate. In this type of machine the crosshead, mounted on tension screws that pass freely through the platen, is fixed during the application of load. Compression loads are applied to specimens placed between the movable platen and the crosshead. When tension loads are desired, the specimen is mounted between the fixed crosshead and an upper crosshead, attached to the platen by compression columns. The top crosshead moves upward when oil is pumped into the cylinder, thus developing a tension load.

In this type of hydraulic machine, the load on the sensitive (fixed) crosshead is always exerted in an upward direction. This load is transmitted by the tension screws on which the sensitive crosshead is mounted to a hydraulic weighing capsule. The pressure on a small quantity of oil in the capsule is transmitted through a hydraulic connection to a Bourdon-tube type of indicator, and the load is read directly from a graduated dial.

For testing long beams an extended platform is used with either mechanical or hydraulic machines. In testing wood it is standard practice to take simultaneous readings of loads and deformations "on the fly," the machine being operated at a uniform rate of strain without interruption from beginning to end of test. This eliminates the effect of a variable time factor on the strength of the wood and facilitates the progress of the work.

Testing machines are usually calibrated to a portion of their capacity before leaving the factory. They should be further calibrated at sufficiently frequent intervals to insure accuracy. For machines in constant use, such verification should be made at intervals of 6 months; when their use is intermittent, calibration should be made every 2 or 3 years.[7]

The size of machine suitable for testing small specimens depends on the kind of tests involved. Machines of 30,000 pounds capacity are sometimes recommended for general testing, but these have been found inadequate for carrying out standard tests in compression parallel to grain, especially on dry material. For endwise-compression tests, machines having a capacity of 50,000 to 100,000 pounds have been found to be much more satisfactory. For other standard static tests, machines of 10,000 pounds capacity are adequate. A number of modern testing machines are provided with several capacity ranges, the lower ranges permitting more accurate determination of load.

---

[7] See Standard methods of verification of testing machines, Serial Designation: E4-47T, 1947 *Book of Standards*, Am. Soc. Test. Mat., Philadelphia, Pt. II.

SPEED OF TESTING MACHINE

In instructions for making static tests the rate of application of the stress, that is, the speed of the machine, is given because the strength of wood varies with the rate at which the fibers are strained. The speed of the loading mechanism of the testing machine is practically never exactly constant, owing to mechanical defects of the apparatus and variations in the speed of the motor (or rate of oil delivery by the pump), but, as long as it does not vary more than 25 percent from that specified for a given test, the results will not be appreciably affected. In fact, a change in speed of 50 percent will not cause the strength of the wood to vary more than 2 percent.[8]

Following are the formulas used in determining the speed of the movable head of the machine in inches per minute (n):

(1) For endwise compression $n = Zl$

(2) For beams (center loading) $n = \frac{Zl^2}{6d}$

(3) For beams (third-point loading) $n = \frac{Zl^2}{5.4d}$

Z = rate of fiber strain per inch of fiber length, inches per minute
l = span of beam or length of compression specimen
d = depth of beam

The values commonly used for Z are as follows:

Bending large beams	$Z = 0.0007$
Bending small beams	$Z = 0.0015$
Endwise compression—large specimens	$Z = 0.0015$
Endwise compression—small specimens	$Z = 0.003$

---

[8] See Harry Donald Tiemann, The effect of the speed of testing upon the strength of wood and the standardization of tests for speed, *Proc. Am. Soc. Test. Mat.*, Philadelphia, Vol. 8, 1908, pp. 541–57.

Example. At what speed should the crosshead move to give the required rate of fiber strain in testing a small beam 2 inches x 2 inches x 30 inches? (Span = 28 inches.) Substituting these values in equation 2 above yields

$$n = \frac{0.0015 \times 28^2}{6 \times 2} = 0.098, \text{ or approximately 0.1 inch per minute}$$

DESCRIPTION OF TESTS

Static Bending—Large Beams[9]

Apparatus. A static testing machine, with a special crosshead for third-point loading and a long platform bearing knife-edge supports, is required, together with a wire and scale for measuring deflection, and suitable bearing blocks, bearing plates, and rollers (see Fig. 64).

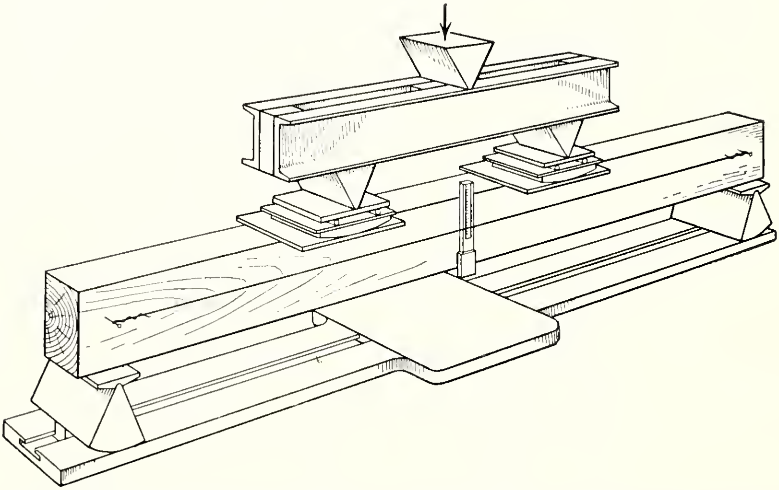


FIG. 64. Static-bending test on a large beam. Note arrangement of wire and scale for measuring deflection; also method of applying load at "third-points."

Preparing the Material. The material tested may be selected from standard sizes and grades of beams and timbers in common use, or it may be specially cut for the purpose from standing trees. The size of test specimens naturally depends on the available sizes used for the particular purpose under consideration, and on the available material. Timbers 8 by 16 inches or 6 by 12 inches in nominal cross section and 16 feet long have been extensively used as representative of bridge stringer sizes. The timbers are surfaced on four sides and squared at the ends before being tested. They are then weighed, and length and actual depth and width at the center are measured. Weights should be to the nearest pound, lengths to the nearest 0.1 inch, and cross-sectional dimensions to the nearest 0.01 inch.

---

[9] See Standard methods of conducting static tests of timbers in structural sizes, footnote 1, for working plan and further details of procedure for the three major tests made on material of this class.

Marking, Photographing, and Sketching. The butt end of the beam is marked *A* and the top end *B*. While looking at the butt end, the upper face (to which the load is applied) is marked *a*, the right-hand face *b*, the bottom face *c*, and the left-hand face *d*.

Air-dried timbers are photographed on four sides both before and after test; unseasoned timbers after test only. The middle of the length of the beam, the load and support points, and the order of occurrence of the failures are indicated so as to show in the photograph; if necessary to bring them out in the photograph the failures are penciled or pointed.

Sketches are made of each face and end, showing (1) size, location, and type of knots, checks, shakes, splits, and cross grain; (2) distribution of heartwood and sapwood; (3) occurrence of crook, bow, cup, twist, and other irregularities that may be present; and on the ends, (4) the arrangement of the growth rings and the location of the pith, when present. Record is also made of the number of rings per inch and the proportion of summerwood (late wood) at each end.[10]

The number of rings per inch and the proportion of late wood should be determined over a 3-inch portion of a radial line representative of the average growth on the cross section (see Basic Provisions for Grading Rules for Structural Lumber, page 223, for location of this radial line in Douglas fir and southern pine). The average number of rings per inch is the total number of rings divided by the length of the line crossing them. The

---

[10] See Fig. 65 for method of recording location and type of defects and other pertinent data. Cross-section paper or quadrille-ruled notebook paper is recommended for conveniently making the sketch of the beam to scale.

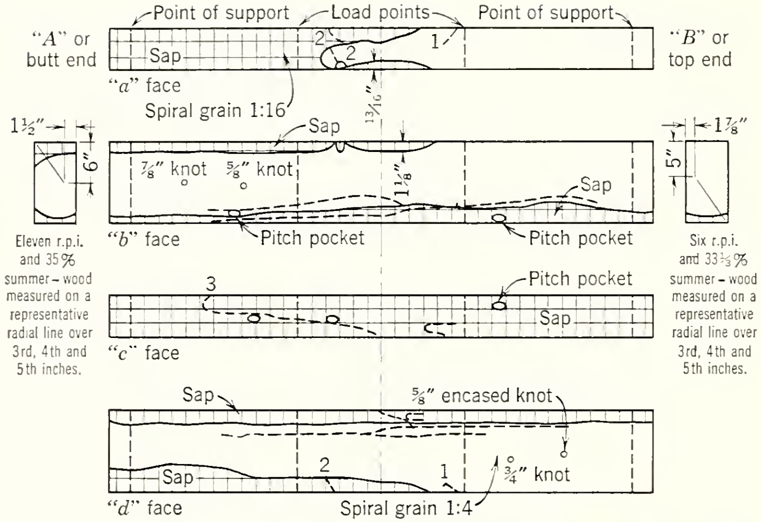

Point of support
Load points
Point of support
"A" or butt end
"B" or top end
Sap
2
2
1
"a" face
Spiral grain 1:16
$13/16''$
$1\frac{1}{2}''$
6"
Sap
$\frac{7}{8}''$ knot
$\frac{5}{8}''$ knot
$1\frac{1}{8}''$
Sap
$1\frac{7}{8}''$
5"
"b" face
Pitch pocket
Pitch pocket
Eleven r.p.i. and 35% summer-wood measured on a representative radial line over 3rd, 4th and 5th inches.
Six r.p.i. and $33\frac{1}{3}$% summer-wood measured on a representative radial line over 3rd, 4th and 5th inches.
3
Pitch pocket
Sap
"c" face
Sap
$\frac{5}{8}''$ encased knot
Sap
2
1
$\frac{3}{4}''$ knot
"d" face
Spiral grain 1:4

Diagram Prepared by Forest Products Laboratory

FIG. 65. Sketch of structural-size timber showing method of recording location and type of defects and other pertinent data. Broken lines indicate test failures, and the accompanying numbers their order of occurrence.

proportion of late wood is equal to the sum of the widths of the late wood crossed by the line, divided by the length of the line. Rings per inch should be taken to the nearest 0.1; late wood to the nearest 1 percent.

Since in large beams a great variation in rate of growth and relative amount of late wood may occur in different parts of the section, it is advisable to consider the cross section in three volumes, namely, the upper and lower quarters and the middle half. The determination should be made on each volume separately and the average for the entire cross section obtained from these results.

At the conclusion of the test the failures, as they appear on each surface, are traced on the sketches, being numbered in the order of their occurrence. If the beam is subsequently cut up and used for other tests an additional sketch may be desirable to show the location of each test piece.

Adjusting Specimen in Machine. The timber is placed in the machine with the face marked *a* on the top and with the ends projecting equally beyond the knife edges which are used as supports. The span, or distance between supports, will vary according to the purpose of the tests and the length of the test specimen; for 16-foot timbers a span of 15 feet is used. Third-point loading is used, that is, the load applied at two points one-third the span of the beam apart (see Fig. 66). Under this type of loading, maximum stress in the surface fibers is uniform throughout the central third of the beam (see Fig. 11), a condition that facilitates the study of the influence of defects.

Knife edges rigidly attached to an auxiliary beam, which in turn is hinged by a knife edge, are used in applying the load.

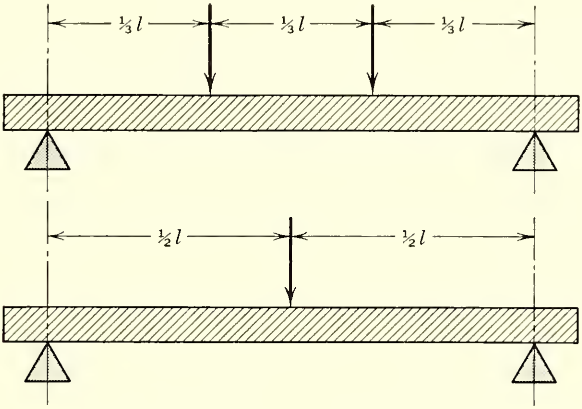


Fig. 66. Two methods of loading a beam, namely, third-point loading (upper) and center loading (lower).

The supporting knife edges should preferably be of the half-rocker type, and should be so placed as to rock outward; to prevent accident or damage from their being thrust suddenly outward on failure of the specimen, they should be fastened together by means of a slack chain or cable. Metal bearing plates, 6 inches wide and not less than $\frac{1}{2}$ inch in thickness and extending entirely across the bottom face of the beam, should be used over the supporting knife edges. In order to prevent crushing of the fiber at the points where the stress is applied, it is necessary to use bearing blocks of maple or other hardwood of the form and size shown in Fig. 67, placed with the convex surface toward the beam. Further, a steel plate about $\frac{5}{32}$ inch in thickness and slightly wider than the beam should be placed between the bearing block and the beam. Metal bearing plates and rollers should be used between each bearing block and the corresponding knife edge of the crosshead, in order to allow for the shortening due to flexure; if the supporting knife edges are of the full-rocker type rather than the half-rocker type recommended previously, rollers should be placed under one loading knife edge only. The plates between rollers and knife edges should be not less than 1¼ inches in thickness (see Fig. 64).[11]

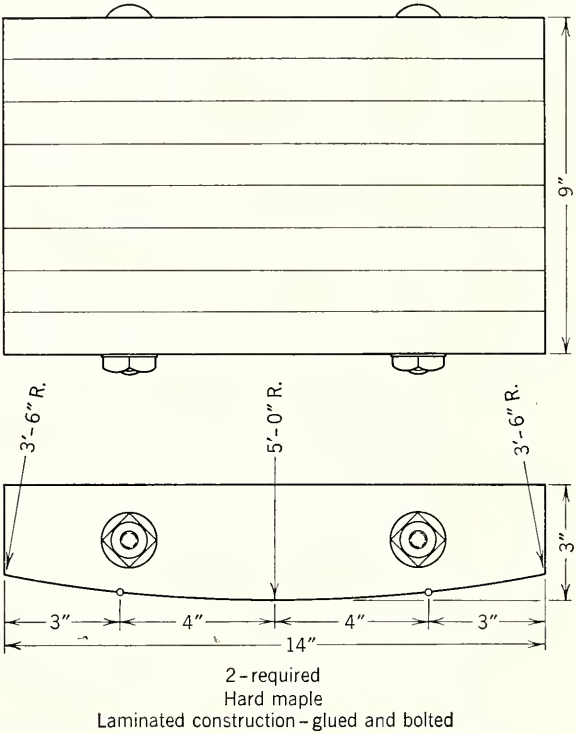


Fig. 67. Details of bearing block for timbers 12 to 16 inches in depth, when tested in third-point loading over a 15-foot span. Two such bearing blocks are used.

---

[11] The details given in this paragraph apply specifically to timbers in structural sizes, such as 6-by-12-inch and 8-by-16-inch bridge stringers, tested over a 15-foot span. For information regarding material of other sizes see Standard methods of conducting static tests of timbers in structural sizes, footnote 1.

Parallelism should be obtained at the bearing points in every instance. In the case of warped beams, wedges or shims should be used between the plate and the loading or supporting knife edges, or both, as may be necessary to obtain an even bearing before the load is applied.

Measuring the Deflection. The method of measuring the deflection of the beam at the center of the span should be such that any compression at the points of support or at the application of the load will not affect the reading. This may be accomplished by driving a small nail near each end of the beam, the exact location being on the neutral plane and vertically above each knife-edge support. Between these nails a fine wire is stretched free of the beam and kept taut by means of a rubber band or coiled spring on one end. Behind the wire, at a point on the beam midway between the supports, a steel cable graduated to hundredths of an inch is fastened vertically by means of thumbtacks or small screws passing through holes in it. Attachment should be made on the neutral plane (see Figs. 10 and 64). Where special refinement is desired, deflection readings may be taken simultaneously on both sides of the beam, the wires being supported over free-running pulleys and held taut with small suspended weights.

The first reading is made when the scale beam is balanced at zero load; subsequent readings are made at regular increments of the load, which is applied continuously with a uniform motion of the movable head (see Speed of Testing Machine, page 285). If desired, however, the load may be read at regular increments of deflection. The deflection readings should be to the nearest 0.01 inch. To avoid error due to parallax, the readings may be taken by means of a reading telescope about 10 feet distant and approximately on a level with the wire. A mirror fastened to the scale will increase the accuracy of the readings if the telescope is not used. As in all tests on timber, the strain must be continuous to rupture, not intermittent, and readings must be taken "on the fly." In beam-type machines the weighing beam is kept balanced after the proportional limit is reached. The maximum load and at least one point beyond it are noted.

Log of the Test. The proper log sheet for this test consists of a piece of cross-section paper with space at the margin for notes (see Fig. 69). The loads in some convenient unit (1000 to

10,000 pounds, depending on the dimensions of the specimen) are entered as ordinates, the corresponding deflections as abscissas. The increments of load should be chosen so as to furnish at least 10 points on the load–deflection diagram before the proportional limit is reached; ordinarily increments of 2000 pounds are satisfactory with material of structural size.

As readings of the wire on the scale are made, they are entered directly in their proper place on the cross-section paper. In many cases a test should be continued until complete failure results. Load and deflection readings should be taken at the points where the various failures or sudden changes occur, and reference to them should be made on the stress–strain diagram, even though they may not occur at one of the regular load or deflection increments. A brief description of the type and manner of failures is made on the margin of the log sheet, and their form and position are traced on the sketches, with notations as to the order of their occurrence.

Disposal of Specimen. Two one-inch sections are cut from the region of failure to be used in determining the average moisture content and the distribution of moisture (see Moisture Determination, page 280). The remainder of the section of the beam containing the failure is held for examination and reference until analysis of the data has been completed. A 2-inch section is also retained for purposes of identification and future reference, and for possible microscopic study; the number of rings per inch and proportion of summerwood should be recorded for this section. The remainder of the beam may be cut into suitable specimens for major compression tests and into small clear specimens for the miscellaneous minor tests.

Calculating the Results. The formulas used in calculating the results of tests on large rectangular simple beams loaded at third-points of the span are as follows:

$$(1)\quad J = \frac{0.75P}{bd} \qquad\qquad (3)\quad R = \frac{l(P + 0.75W)}{bd^2}$$

$$(2)\quad r = \frac{l(P_1 + 0.75W)}{bd^2} \qquad\qquad (4)\quad E = \frac{P_1 l^3}{4.7Dbd^3}$$

$$(5)\quad S = \frac{0.87P_1D}{2V}$$

where b,d,l = breadth, depth, and span of specimens, inches
D = total deflection at proportional limit, inches
P = maximum load, pounds
P_1 = load at proportional limit, pounds
E = modulus of elasticity, pounds per square inch
r = fiber stress at proportional limit, pounds per square inch
R = modulus of rupture, pounds per square inch
S = elastic resilience or work to proportional limit, inch-pounds per cubic inch
J = greatest calculated longitudinal shear, pounds per square inch
V = volume of beam between supports, cubic inches
W = weight of the beam, pounds

In large beams the weight should be taken into account in calculating the fiber stress. In formulas 2 and 3, three-fourths of the weight of the beam is added to the load for this reason.[12] The results should be tabulated on a suitable computation data card (see Fig. 71).

Static Bending—Small Beams

Apparatus. An ordinary static testing machine, a steel I beam bearing two adjustable knife-edge supports to rest on the platform, suitable bearing plates and rollers, a wooden bearing block, and a deflectometer are required (see Fig. 68).

Preparing the Material. Static-bending tests are most commonly made on nominal 2-by-2-by-30-inch specimens free from defects, although small knots and other similar defects may be admitted when their location is such that it is certain they will not in any way influence the failure or otherwise affect the strength of the specimen. This material may be taken from logs or bolts specifically cut for the purpose, from large beams after failure, or from other sources, depending on the object of the tests. If they are to be tested unseasoned, the specimens should be kept close piled and covered with damp sawdust in a framed pit or other suitable container, or stored in some other satisfactory manner until needed. In any case the period of storage should be as short as possible. Just prior to testing, the beams are cut to length and surfaced on all four sides, care being taken that they are not damaged by the rollers of the surfacing machine.

---

[12] A uniformly distributed load, such as the weight of a beam, is equivalent to a load three fourths as great when applied at the third-points.

Sketching and Recording Data. Sketches are made on the log sheet (see Fig. 69) of each end of the specimen to be tested to show the character of growth; after testing, the manner of failure is shown on all four sides. The specimens are carefully weighed in grams, and the actual depth and width at the center and the length are measured to the nearest 0.01 inch. Data are also recorded as to the number of rings per inch and, when possible, the percentage of summerwood; these characteristics are determined along a radial line representative of the average growth of the cross section. Record is also made of the proportion of sapwood. The average moisture content is determined immediately after testing from a 1-inch section cut near the failure (see Moisture Determination, page 280).

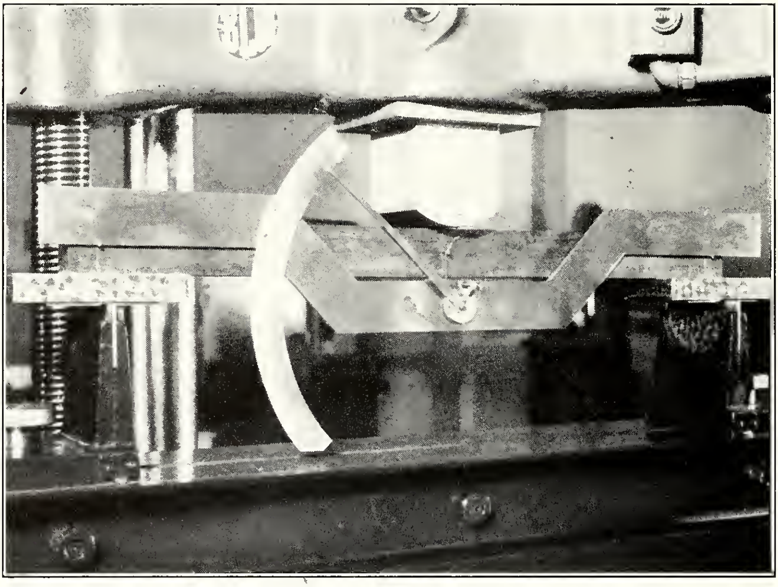


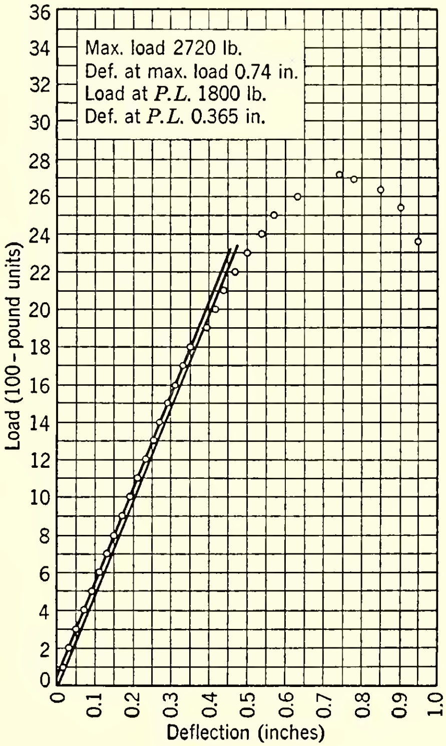
FIG. 68. Static-bending test on a small beam. Note the use of deflectometer with indicator and scale for measuring the deflections; also roller-bearing unit between the beam and supporting knife edges.

TIMBER TEST LOG SHEET

TIMBER TESTING LABORATORY YALE SCHOOL OF FORESTRY

Project No. *PP1* Ship. No. *1* Stick No. Collector's No. *36*
Laboratory No. *712* Piece No. Mark *B* Yale No. *15769*
Date *2/10/49*
Scientific name *Xylopia Staudtii* Family *Annonaceae*
Common name *Drehn* Region *Liberia*
Grade *Clear*
Kind of test *Static Bending*
Loading *Center*
Span *28″*
Distance between collars
Width of plate
Machine *17235*
Mach. speed *0.105* in. per min.
Depth of specimen *1.97″*
Width *1.96″*
Length *30.20″*
Cross section
Weight *1016 gms.*
Rings per inch
Sapwood *0%*
Summerwood
Condition *Air-dried*

Moisture content *9%*
Kind of failure *Splintering tension*
Remarks



Max. load 2720 lb.
Def. at max. load 0.74 in.
Load at *P.L.* 1800 lb.
Def. at *P.L.* 0.365 in.

Sketch

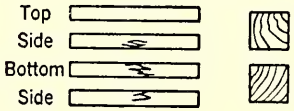


FIG. 69. Sample log sheet for static-bending test on small clear beam.

Adjusting Specimen in Machine. Center loading and a span length of 28 inches are used. The specimen is correctly centered over the two supporting knife edges, being placed so that the load will be applied to the tangential (flat-sawed) surface nearest the pith. Bearing plates and rollers, having a total thickness of approximately 1¼ inches, are placed between the beam and each supporting knife edge, thus bringing the neutral plane of the test specimen about 2¼ inches from the knife edges. The knife edges are adjustable laterally to permit adjustment for slight twist or other form of warp in the specimen. Between the crosshead of the machine and the specimen is placed a bearing block of maple or other hardwood, the lower surface of which is curved in a direction along the beam; this curvature should be slightly less than that of the beam at rupture, in order to prevent

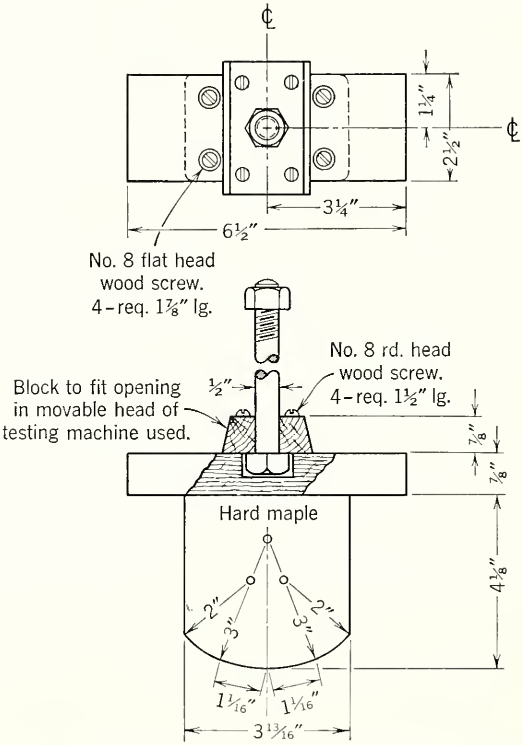

℄
1¼"
2½"
℄
3¼"
6½"
No. 8 flat head wood screw. 4-req. 1⅞" lg.
No. 8 rd. head wood screw. 4-req. 1½" lg.
Block to fit opening in movable head of testing machine used.
½"
⅞"
⅞"
Hard maple
4⅛"
2"
2"
3"
3"
1 1/16"
1 1/16"
3 13/16"

FIG. 70. Details of bearing block for static-bending tests on small clear specimens.

the edges from crushing into the fibers of the test piece. Details of the form and size of bearing block are shown in Fig. 70.

Measuring the Deflection. Deflections of the neutral plane at the center of the length of the beam are taken with respect to points in the neutral plane directly above the supports. The method of measuring deflection of large beams can be used for small sizes, but, because of the shortness of the span and the consequent slight deformation in the small specimens, it is not sufficiently accurate for the refined readings that should be taken within the proportional limit. After the proportional limit has been reached, less refinement is necessary, readings being taken to the nearest 0.01 inch, and this method gives satisfactory results. The special deflectometer shown in Fig. 68 is recommended for readings within the proportional limit, that should be taken to 0.001 inch. It is, however, limited in capacity to a total deflection of 1 inch. This deflectometer rests on two small nails driven in the beam at the neutral plane and vertically above the supports. The fine wire on the wheel at the base of the indicator is attached to another small nail driven in the beam on the neutral plane midway between the end nails. All three nails should be in place before the beam is put into the machine. The indicator is adjustable by means of a thumbscrew at the base and is set at zero for the initial reading. This type of deflectometer may be modified to use an Ames dial in place of the pointer. The load is applied continuously throughout the test at a rate of 0.10 inch per minute (see Speed of Testing Machine, page 285), and readings are taken "on the fly."

Log of the Test. The log sheets used for small beams (see Fig. 69) are the same as for large sizes, and the procedure is practically identical. The load–deflection diagram is continued to or beyond the maximum load in all tests; in one third of the tests it should be continued to 6-inch deflection, or until the specimen fails to support a load of 200 pounds. Deflection readings for equal increments of load (50 or 100 pounds) are taken until well beyond the proportional limit, after which the load is read for each 0.1-inch deflection. The load and deflection at first failure, the maximum load, and any points of sudden change should be shown on the diagram, even though they do not occur at one of the regular load or deflection increments.

After the slope of the load–deflection curve below the proportional limit has been established, this portion of the curve is redrawn as a parallel line passing through the origin of coordinates. The adjusted curve permits direct reading of the true deflection associated with a particular load and is used in calculating modulus of elasticity and work to proportional limit.

A brief description of the failure and the nature of any defects is entered on the log sheet. Bending failures are classified according to the appearance of the fractured surface and according to the manner in which the failure develops. The fractured surfaces may be roughly divided into *brash* and *fibrous*, the term "brash" indicating an abrupt failure and term "fibrous" indicating a fracture showing splinters. The test failures are classified and described as (1) simple tension, (2) cross-grained tension,[13] (3) splintering tension, (4) brash tension, (5) compression, and (6) horizontal shear (for descriptions and illustrations of these terms see pages 48–52 and Fig. 15). If two or more kinds of failure develop, all should be described in the order of their occurrence.

Calculating the Results. The formulas used in calculating the results of tests on small rectangular simple beams are as follows:

$$(1)\quad J = \frac{0.75P}{bd} \qquad\qquad (3)\quad R = \frac{1.5Pl}{bd^2}$$

$$(2)\quad r = \frac{1.5P_1l}{bd^2} \qquad\qquad (4)\quad E = \frac{P_1l^3}{4Dbd^3}$$

$$(5)\quad S = \frac{P_1D}{2V}$$

$$(6)\quad S_1 = \frac{\text{area under load–deflection curve to maximum load,}^{14}\ \text{inch-pounds}}{V}$$

$$(7)\quad S_2 = \frac{\text{total area under load–deflection curve, inch-pounds}}{V}$$

In addition to the legend used on page 293,

S_1 = work to maximum load, inch-pounds per cubic inch
S_2 = total work, inch-pounds per cubic inch

The weight of the beam itself is disregarded.

---

[13] The test is culled if the slope of the cross grain deviates more than 1 in 20 from the longitudinal edges of the specimen.

[14] Use of a planimeter is recommended for the measurement of areas involved in the determination of work values.

The results should be tabulated on a suitable computation data card (see Fig. 71).

Impact Bending

Apparatus. There are several types of impact-testing machines.[15] One of the most simple and efficient is the so-called Hatt-Turner machine used by the U. S. Forest Service, which is a modification of the Purdue University impact machine[16] (see Fig. 72).

This machine consists essentially of a "hammer" sliding between vertical guide columns. The hammer is raised by an electric magnet which is pulled up or lowered as desired by a mechanism driven by a motor mounted on the top of the columns. Current for the magnet coil is furnished by a small dynamo driven by the same motor. The hammer is let drop when the magnetic circuit is broken with the throwing of a switch on the magnet by a tripping pin. This tripping pin slides on a scale attached to one of the guide columns and is capable of being set at any desired position. The scale itself is movable vertically for adjustment. The base of the machine consists of a heavy casting to which the guide columns are bolted and whose upper face is slotted to receive attachments for supporting the specimen. Mounted on the base of the machine and near the guide columns is a brass drum or hollow cylinder. This drum is free to rotate about a vertical axis and is so positioned that a stylus carried by the hammer can be pressed against its surface by a spring. An arrangement is provided for mounting a tuning fork in such a manner that a stylus fixed to one of its prongs may be pressed against the drum. The machine is equipped with hammers weighing 12½, 25, 50, 100, and 200 pounds. A detachable, rounded striking block may be fixed to the lower end of each of

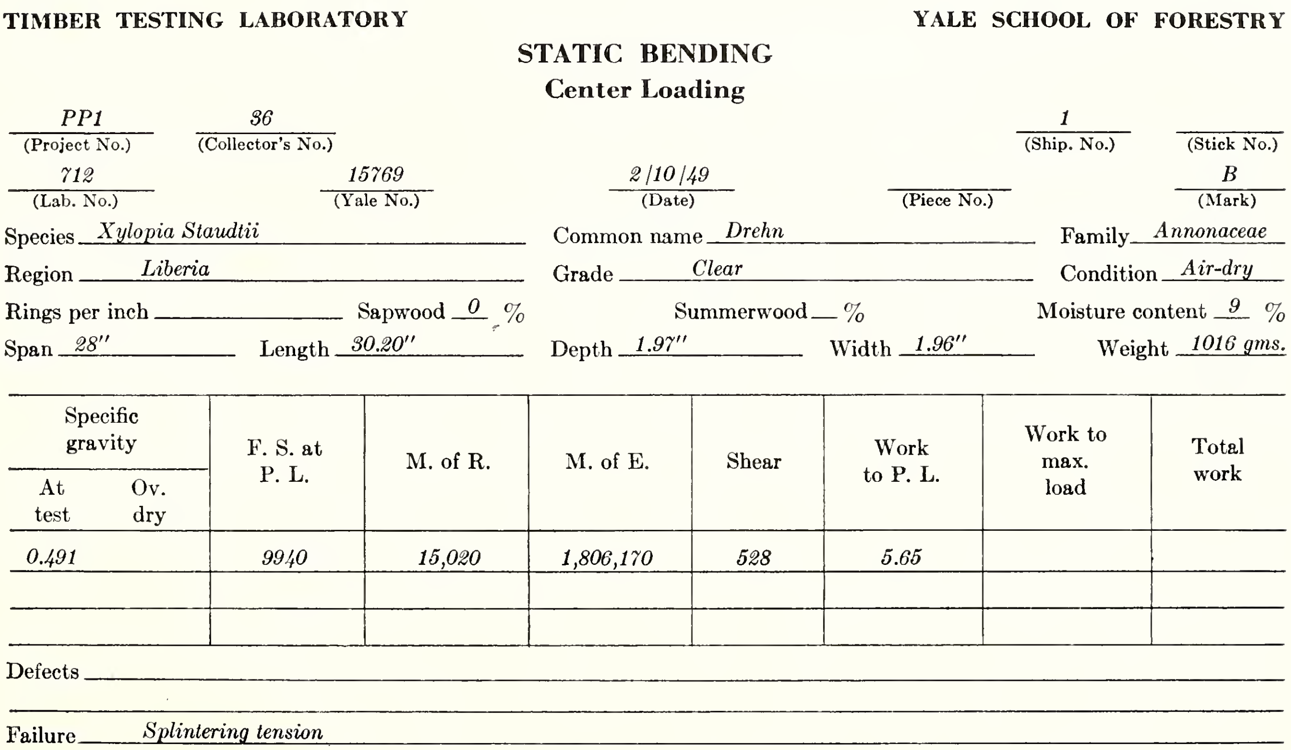
---

[15] See Thomas R. C. Wilson, Impact tests of wood, *Proc. Am. Soc. Test. Mat.*, Philadelphia, Vol. 22, Pt. 2, pp. 55–70, 1922.

W. K. Hatt and W. P. Turner, The Purdue University impact machine, *Proc. Am. Soc. Test. Mat.*, Philadelphia, Vol. 6, pp. 462–75, 1906.

The machine for toughness tests, described on pages 321–39 is an extremely simple form of impact-testing machine of the single-drop type, especially designed for acceptance tests of wood intended for exacting uses, such as airplane and propeller construction.

[16] The following description of the Hatt-Turner machine and the method of test is taken largely from Wilson, footnote 15.



TIMBER TESTING LABORATORY **YALE SCHOOL OF FORESTRY**

STATIC BENDING

Center Loading

PP1 (Project No.) *36* (Collector's No.) *1* (Ship. No.) (Stick No.)

712 (Lab. No.) *15769* (Yale No.) *2/10/49* (Date) (Piece No.) *B* (Mark)

Species *Xylopia Staudtii* Common name *Drehn* Family *Annonaceae*

Region *Liberia* Grade *Clear* Condition *Air-dry*

Rings per inch ____ Sapwood *0* % Summerwood __ % Moisture content *9* %

Span *28″* Length *30.20″* Depth *1.97″* Width *1.96″* Weight *1016 gms.*

Specific gravity		F. S. at P. L.	M. of R.	M. of E.	Shear	Work to P. L.	Work to max. load	Total work
At test	Ov. dry							
0.491		*9940*	*15,020*	*1,806,170*	*528*	*5.65*		

Defects ____

Failure *Splintering tension*

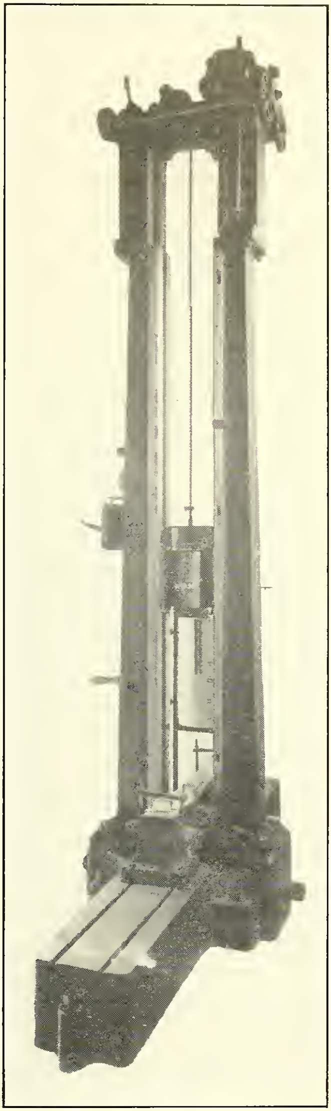
FIG. 71. Sample computation data card for static-bending test on small clear beam.

these hammers for use in flexure tests. The curvature of this metal striking block corresponds to that of the bearing block used for static-bending tests on small beams (see Fig. 70). A similar flat-faced block is available for use in compression tests. The hammer can be dropped from a height of approximately 6 feet; consequently, the capacity of the machine is 75, 150, 300, 600 or 1200 foot-pounds, depending on which of the hammers is used. The weight of the entire machine is approximately 5500 pounds.

In flexure tests the blow of the hammer is received at the center of a beam of simple span. Each end of the beam is set loosely in a "shoe," which is free to turn on supporting knife edges of rounded form. The shoes are of sufficiently small mass that the energy absorbed as they turn slightly with the deflection of the beam is negligible.

Two kinds of flexure-impact tests have been made on this machine: (1) Single-drop tests in which the specimen is completely fractured by a single blow; and (2) increment-drop tests in which the hammer is allowed to fall from successively increasing heights until failure occurs. The latter type is recognized as the standard impact test. (For description of the single-drop test see Wilson, footnote 15.)

Preparing the Material. Nominal 2-by-2-by-30-inch specimens, free from defects, are prepared in the same manner as for static-bending tests.



U. S. Forest Service Photo

FIG. 72. Hatt-Turner impact machine, showing method of conducting impact-bending tests.

Sketching and Recording Data. Sketches are made and measurements and other data recorded on suitable log sheets and computation data cards.[17]

Adjustment in Machine. The specimen is centered over the supporting knife edges, which have a span of 28 inches. It is placed so that the load will be applied through the striking block to the tangential (flat-sawed) surface nearest the pith.

Method. After the specimen is placed in position, the hammer (without the magnet) is allowed to rest on it while the drum is rotated, and the stylus attached to the hammer traces a datum line on the record sheet mounted on the drum. The hammer is then raised for the first drop, and, as it falls on the stick, the operator turns the drum slightly while the hammer is coming to rest. This is done in order to get separate and distinct stylus traces of (1) the height of drop (as long as this does not exceed the height of the drum), (2) the deflection produced by the drop, and (3) the set, or the position of the hammer after it has come to rest on the stick. Such a record is taken for each drop until first failure occurs and should afford data from which the exact height of drop can be scaled for at least the first four falls (see Fig. 73). After first failure, the recording drum is swung clear of the stylus and loading is continued. The first drop is 1 inch, and the increase is by increments of 1 inch until a height of 10 inches is reached, after which increments of 2 inches are used until complete failure occurs or 6-inch deflection is obtained.

A 50-pound hammer is used when, with drops up to the capacity of the machine (about 68 inches for the small Hatt-Turner impact machine), it is practically certain that complete failure or 6-inch deflection will result for all specimens of a species; in all other cases a 100-pound hammer is used.

Results. The tracing on the graphic drum record (Fig. 73) represents the actual deflection of the stick and the subsequent rebounds for each drop until first failure occurred. The distance from the lowest point in each case to the datum line is measured, and its square in tenths of a square inch is entered as an abscissa on cross-section paper, with the height of drop in inches as the ordinate. The proportional limit is that point of the diagram where the square of the deflection begins to increase more rapidly

---

[17] See Standard methods of testing small clear specimens of timber, footnote 1. Figs. 34 and 35 of Appendix.

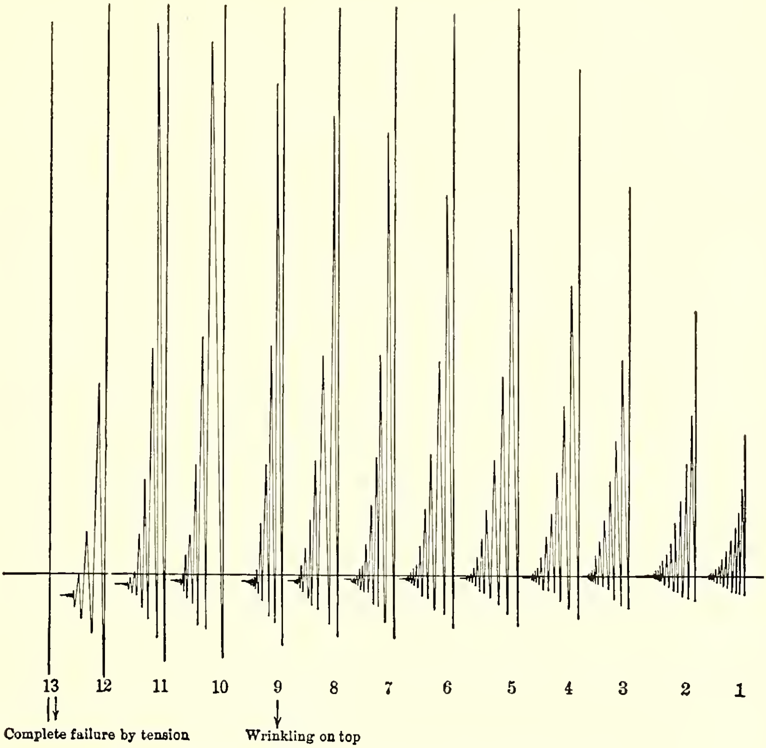


Fig. 73. Drum record of impact-bending test.

than the height of the drop. The difference between the datum line and the final resting point after each drop represents the set the material has received. The height of drop causing complete failure, or a 6-inch deflection, is observed for each specimen. The failure is sketched on the log sheet and described as for static bending.

The formulas used in calculating the results of impact tests in bending, when the load is applied at the center up to the proportional limit, are as follows:

$$(1) \quad r = \frac{3WHl}{Dbd^2} \qquad\qquad (2) \quad E = \frac{WHl^3}{2D^2bd^3}$$

$$(3) \quad S = \frac{WH}{V}$$

H = height of drop of hammer, including deflection, inches
S = elastic resilience, inch-pounds per cubic inch
W = weight of hammer, pounds
Remainder of legend as on page 293.

The results should be tabulated on suitable computation data cards.

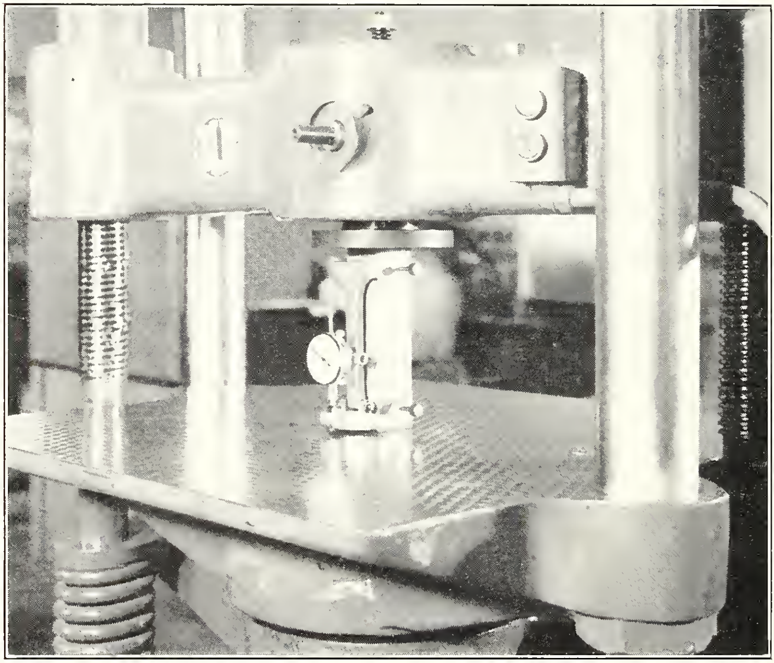


FIG. 74. Testing a small specimen in compression parallel to the grain. Note spherical bearing block and compressometer used for measuring deformation.

Compression Parallel to Grain

Apparatus. A universal static testing machine, a spherical bearing block, and a compressometer are required (see Fig. 74).

Preparing the Material. Tests in compression parallel to the grain are most frequently made on two classes of material: (1) Small specimens free from defects, and (2) 6-by-6-by-24-inch specimens cut from large timbers after static-bending tests and containing such defects as are normal to the timbers.[18] The small clear specimens are either 2 by 2 by 8 inches in size or of the special form and size shown in Fig. 75; the latter form, of reduced cross section, usually requires less care preparatory to test in order to prevent crushing at the ends than does the former. The specimens with uniform cross section throughout their length are surfaced on all four sides, and both ends are squared smoothly and evenly.

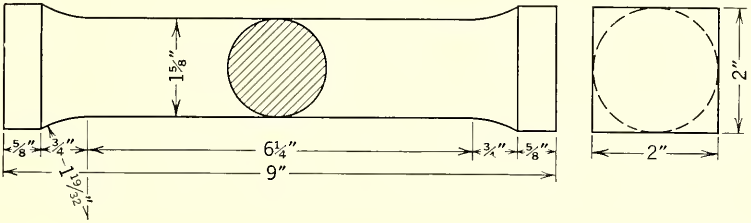


FIG. 75. Special form of compression-parallel-to-the-grain test specimen.

In order to obtain satisfactory and uniform results, it is necessary that the failures be made to develop in the body of the specimen. With specimens of uniform cross section, this result can best be obtained when the ends are at a very slightly lower moisture content than the body. With unseasoned material it will usually suffice to close-pile the specimens, cover the body with a damp or wet cloth to prevent drying from the sides, and expose the ends for a short time. For air-dry material, it may sometimes be advisable, should the failures in test indicate that a slight end drying is necessary, to pile the specimens in a similar manner and place them in a desiccator.

Sketching and Recording Data. Sketches are made of each end of every specimen to show the character of growth. The specimen is carefully weighed and measured, and the rate of growth and the proportions of sapwood and summerwood (when

---

[18] For details of test on large specimens see Standard methods of conducting static tests of timbers in structural sizes, footnote 1, pp. 14–15.

In addition, tests are made on short, intermediate, and long columns, of nominal 12-by-12-inch cross section. For procedure see J. A. Newlin and J. M. Gahagan, *Tests of large timber columns and presentation of the Forest Products Laboratory column formula,* U. S. Dept. Agr. Tech. Bul. 167, Washington, 1930, pp. 39–40.

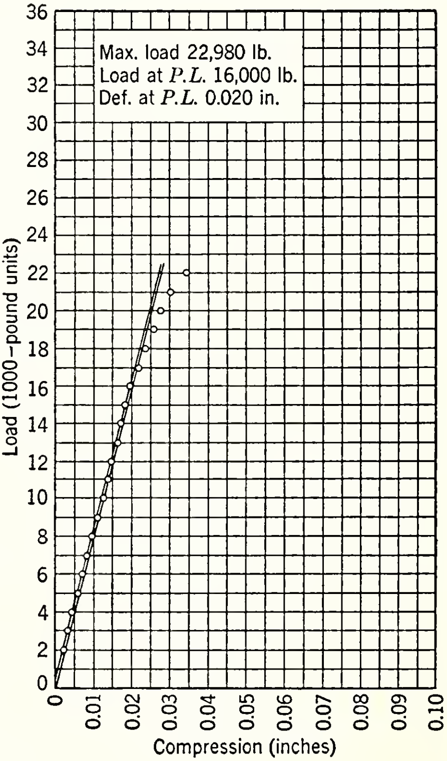
TIMBER TEST LOG SHEET

TIMBER TESTING LABORATORY YALE SCHOOL OF FORESTRY

Project No. *PP1* Ship. No. *1* Stick No. Collector's No. *72*
Laboratory No. *940* Piece No. Mark Yale No. *15804*
Date *6/21/49*
Scientific name *Terminalia superba* Family *Combretaceae*
Common name *Baye* Region *Liberia*
Grade *Clear*
Kind of test *Comp. ‖ grain*
Loading
Span
Distance between collars *6″*
Width of plate
Machine *17235*
Mach. speed *0.024* in. per min.
Depth of specimen
Width
Length *7.84″*
Cross section *1.84″ × 1.88″*
Weight *305 gms.*
Rings per inch
Sapwood *0%*
Summerwood
Condition *Air-dry*

Moisture content *9%*
Kind of failure *Shearing*

Remarks


Max. load 22,980 lb.
Load at *P.L.* 16,000 lb.
Def. at *P.L.* 0.020 in.

Sketch

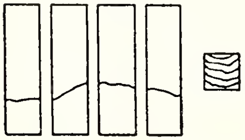


FIG. 76. Sample log sheet for compression-parallel-to-the-grain test.

discernible) are determined, as in bending tests. In the large specimens all defects should be described. After testing, the manner of failure is shown on sketches of all four sides of the specimen, and the various parts of the failure are numbered in the order of their occurrence. The moisture content is determined from a sample 1 inch long taken from near the failure, as described under Moisture Determination (page 280). All data are recorded on the log sheets (see Fig. 76).

Adjusting Specimen in Machine. The compressometer, which is used on the small clear specimens only, is adjusted to the test specimen with a 6-inch central gage length (distance between collars) (see Fig. 74). When the special form of specimen shown in Fig. 75 is used, strain is measured over the central 4-inch gage length. A spherical bearing block is used and so adjusted for each test as to obtain a uniform distribution of load over the ends of the specimen.

Measuring the Deformation. With the large-sized specimens only the maximum load is recorded. With small clear specimens, however, deformations are read to 0.0001 inch, and load–compression readings are continued until the proportional limit is well passed as indicated by the curve (Fig. 76).

Log of the Test. The load is applied continuously throughout the test at a speed of 0.024 inch per minute for small clear specimens, or 0.036 inch per minute for the large-sized material. When the compressometer is used, readings are made at regular increments of load (usually 1000 or 2000 pounds), or the load may be read at given increments of compression. In all instances the test is continued until the maximum load is attained. The modulus line, or straight-line portion of the load–deformation curve, is replotted to pass through the origin as described previously in connection with the static-bending test (see Fig. 76).

A brief description of the failure is entered on the log sheet, together with the sketch of it. Compression failures are classified and described according to their appearance, as (1) crushing, (2) wedge split, (3) shearing, (4) splitting, and (5) compression and shearing parallel to the grain (for description and illustration of these types of failure, see page 33 and Fig. 15). The last-named type of failure usually occurs in cross-grained pieces, and such specimens should be culled. Tests in which brooming occurs on the extreme ends in a horizontal plane should also be

TIMBER TESTING LABORATORY **YALE SCHOOL OF FORESTRY**

COMPRESSION PARALLEL TO GRAIN

PP1 (Project No.)	*72* (Collector's No.)		*1* (Ship. No.)	(Stick No.)
940 (Lab. No.)	*15804* (Yale No.)	*6/21/49* (Date)	(Piece No.)	(Mark)

Species *Terminalia superba* Common name *Baye* Family *Combretaceae*

Region *Liberia* Grade *Clear* Condition *Air-dry*

Rings per inch ____ Sapwood *0* % Summerwood ____ % Moisture content *9* %

Length *7.84″* Cross section *1.84″ × 1.88″* Weight *305 gms.*

Specific gravity		Maximum load	Fiber stress at P. L.	Maximum crush. strength	M. of E.	Load at P. L.	Deform. at P. L.
At test	Ov. dry						
0.652		*22,980*	*4624*	*6642*	*1,391,000*	*16,000*	*0.020*

Defects ____

Failure *Shearing*

Fig. 77. Sample computation data card for compression-parallel-to-the-grain test.

culled, since such a condition usually indicates that the ends of the pieces are more moist than the middle. The plane of failure should occur through the body of the specimen in all cases.

Calculating the Results. The formulas used in calculating the results of tests on endwise compression are as follows:

$$(1)\quad C = \frac{P}{A} \qquad\qquad (2)\quad c = \frac{P_1}{A}$$

$$(3)\quad E = \frac{P_1 l}{AD}$$

C = maximum crushing strength, pounds per square inch
c = fiber stress at proportional limit, pounds per square inch
A = area of cross section, square inches
l = distance between centers of collars, inches
D = total shortening or compression at proportional limit, inches

Remainder of legend as on page 293.

The results should be tabulated on suitable computation data cards (see Fig. 77).

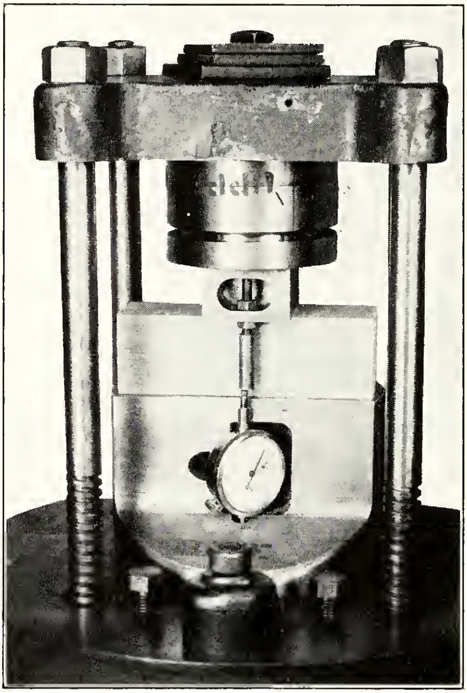
Compression Perpendicular to Grain

Apparatus. A universal static testing machine, a bearing plate, and two compressometers are required (see Fig. 78).

Preparing the Material. Tests are made on two classes of material, namely, (1) 2-by-2-by-6-inch specimens, free from defects, and (2) pieces cut from large timbers after static-bending tests and containing defects normal to them. The latter specimens are 30 inches in length and of the cross section of the major beam. The specimens are surfaced on all four sides and the ends squared.

Sketching and Recording Data. Sketches are made of the ends of each specimen to show the character of growth. Weights, measurements, and data pertaining to the rate of growth, percent of sapwood and summerwood, and moisture content are determined as for compression parallel to grain and are recorded on the log sheet (see Fig. 79). All defects in the large test specimens are described.

Adjusting Specimen in Machine. In the larger specimens the load is applied to a face corresponding to either the loading or supporting face of the static-bending test timbers from which they were cut; the smaller pieces are so placed that the load is applied to a radial (quarter-sawed) surface. The test specimen is laid horizontally on the platform of the machine and so centered that the metal bearing plate, which is placed on its upper surface at equal distances from the ends and at right angles to its length, is immediately beneath the center of the movable head. For the larger specimens this bearing plate is 6 inches wide; for the smaller test pieces 2 inches wide. In all cases the plate projects over the edges of the test piece.



Forest Products Laboratory Photo Reproduced through Courtesy American Society for Testing Materials

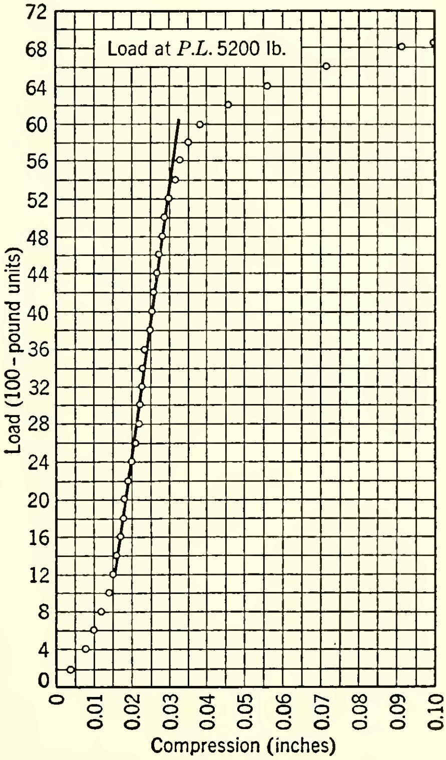
FIG. 78. Test in compression perpendicular to the grain. A second dial for measuring deformation is mounted at the opposite side of the test specimen.

Measuring the Deformation. The compression is measured by

TIMBER TEST LOG SHEET

TIMBER TESTING LABORATORY YALE SCHOOL OF FORESTRY

Project No. *C4* Ship. No. *1* Stick No. *4* Collector's No. ____
Laboratory No. *291* Piece No. ____ Mark *B* Yale No. ____
Date *4/15/49*
Scientific name *Pinus echinata* Family *Pinaceae*
Common name *Shortleaf pine* Region *Southern U. S. A.*
Grade *Clear*
Kind of test *Comp. ⊥ grain*
Loading ____
Span ____
Distance between collars ____
Width of plate *2″*
Machine *17235*
Mach. speed *0.012* in. per min.
Depth of specimen *1.79″*
Width *1.96″*
Length *6.00″*
Cross section ____
Weight *226 gms.*
Rings per inch *5*
Sapwood *100%*
Summerwood *40%*
Condition *Fireproofed and air-dried*
Moisture content *12%*
Kind of failure ____
Remarks *See Treatment sheet II-A for details of treatment*



Sketch

FIG. 79. Sample log sheet for compression-perpendicular-to-the-grain test.

means of suitable compressometers, one type of which is shown in Fig. 78. Deformation readings are taken to 0.0001 inch.

Log of the Test. The load is applied continuously and at uniform speed. For small clear pieces the rate of speed is 0.012 inch per minute, whereas for large specimens it is based on the depth of the specimen.[19] Loading is continued until a compression of 0.1 inch is reached with the small specimens, or, with the larger ones, until the proportional limit is well passed. The test is then discontinued, since the strength of the wood continually increases as the fibers are crushed more compactly together and the maximum load is unattainable.

Calculating the Result. The fiber stress at the proportional limit (c) is the only strength value computed. It is equal to the load at proportional limit (P_1) divided by the area under the plate (B), or $c = P_1/B$.

The results should be tabulated on suitable computation data cards (see Fig. 80).

Hardness[20]

Apparatus. A universal static testing machine and a special hardness tool are required for this test. The tool, which is fitted into the movable head of the machine, consists of a punch with a hardened steel hemispherical end, or "ball," having a diameter of 0.444 inch and giving a projected area of 1 square centimeter. It is fitted with a guard plate, which works loosely until the penetration of the "ball" into the wood has progressed to a depth of 0.222 inch, whereupon it tightens (see Fig. 81). The effect is that of sinking a ball to one-half its diameter into the specimen.

Preparing the Material. The wood to be tested is cut square with the grain into nominal 2-by-2-by-6-inch specimens, which are free from defects.

---

[19] For large specimens the rate of motion of the movable head is determined from the formula:

$$N = 0.0175d^{4/9}$$

where N = the rate of motion of the moving head, inches per minute
d = the depth of specimen, inches

[20] This test is an adaptation of the Janka ball test for surface hardness. See Gabriel Janka, Testing the hardness of wood by means of the ball test, *Proc. Int. Assn. Test. Mat.*, Vol. 23, 1912.

TIMBER TESTING LABORATORY **YALE SCHOOL OF FORESTRY**

COMPRESSION PERPENDICULAR TO GRAIN

C 4			*1*	*4*	
(Project No.)	(Collector's No.)		(Ship. No.)	(Stick No.)	
291		*4/15/49*		*B*	
(Lab. No.)	(Yale No.)	(Date)	(Piece No.)	(Mark)	

Species *Pinus echinata* Common name *Shortleaf pine* Family *Pinaceae*

Region *Southern U. S. A.* Grade *Clear* Condition *Fireproofed and air-dried*

Rings per inch *5* Sapwood *100* % Summerwood *40* % Moisture content *12* %

Width of plate *2″* Length *6.00″* Depth *1.79″* Width *1.96″* Weight *226 gms.*

Specific gravity		Load at P. L.	Fiber stress at P. L.	
At test	Ov. dry			
		5200	*1327*	

See Treatment Sheet II-A for details of treatment

Fig. 80. Sample computation data card for compression-perpendicular-to-the-grain test.

Sketching and Recording Data. The actual cross-section dimensions and length are measured and recorded on suitable data and computation cards (see Fig. 82), together with data as to weight, rings per inch, percent of sapwood and of summerwood, and moisture content. The last-named determination is made immediately after test. A sketch is made of one end of the specimen to show the character of growth.

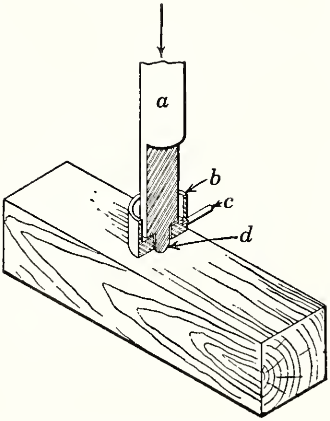


FIG. 81. Diagrammatic sketch of tool used in hardness test.

Method. A test specimen is placed on the platform of the machine, and the end of the punch is forced into the wood at a speed of 0.25 inch per minute. The operator keeps moving the small handle of the guard plate back and forth until it tightens, at which instant the load is read. Two penetrations are made on a tangential surface, two on a radial surface, and two on each end. The choice between the two radial and between the two tangential faces should be such as to give a fair average of the piece. The penetrations should be far enough from the edge to prevent splitting or chipping.

Results. The loads in pounds required to imbed the 0.444-inch "ball" to one-half its diameter on the several surfaces of the specimen, are the only values determined in this test.

Shear Parallel to Grain

Apparatus. A universal static testing machine and a special tool designed for producing single shear are required (see Fig. 83). This shearing apparatus consists of a solid steel frame with a cross bar and setscrews for clamping the block within it firmly in a vertical position. In the center of the frame is a vertical slot in which a square-edged steel plate, equipped with a self-adjusting bearing insert, slides freely. When the testing block is in position, the adjustable bearing plate impinges squarely along the upper surface of the projecting lip of the test specimen,

TIMBER TESTING LABORATORY

HARDNESS

YALE SCHOOL OF FORESTRY

PP1 (Project No.)
18 (Collector's No.)
1 (Ship. No.)
(Stick No.)

522 (Lab. No.)
15752 (Yale No.)
12/6/49 (Date)
(Piece No.)
A (Mark)

Species *Canarium Schweinfurthii*
Common name *Goe-qu-ehn*
Family *Burseraceae*

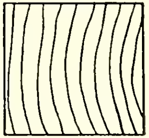
Region *Liberia*
Grade *Clear*
Condition *Air-dry*

Rings per inch ______
Sapwood *0* %
Summerwood __%
Moisture content *7.5* %

Length *6.02"*
Cross section *2.01" × 2.02"*
Weight *184 gms.*

	Specific gravity		Radial surface	Tan-gential surface	End surface
	At test	Ov. dry			
1	*0.482*		*756*	*746*	*911*
2			*746*	*662*	*874*
3					*879*
4					*834*
Avg.			*751*	*704*	*875*

Sketch



Avg. rad. and tang. *728*

Remarks ______

Fig. 82. Sample computation data card for hardness test.

which, as vertical pressure is applied, shears off. The tool is so constructed that a ⅛-inch offset is provided between the inner edge of the supporting surface and the plane along which failure should occur.

Preparing the Material. The tests are made on clear, straight-grained, 2-by-2-by-2½-inch blocks, notched as illustrated in Fig. 86*B*, to produce failure on a 2-by-2-inch surface. These specimens are cut so that the load is applied and the blocks supported on end-grain surfaces. It is important that the upper surface of the projecting lip be sawed exactly parallel to the base of the block. Part of the specimens are cut so that the shearing surface is tangential; the others so that it is radial.

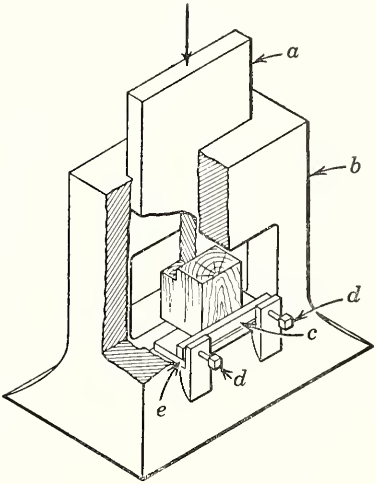


FIG. 83. Diagrammatic sketch of tool for shear-parallel-to-the-grain test.

In designing a shearing specimen it is necessary to take into consideration the proportions of the area of shear, since, if the length of the portion to be sheared off is too great in the direction of the shearing face. failure would occur by compression before the piece would shear. Inasmuch as the endwise-compressive strength is sometimes not more than five times the shearing strength, the shearing surface should, in general, be less than five times the surface to which the load is applied. This condition is fulfilled in the specified specimen.

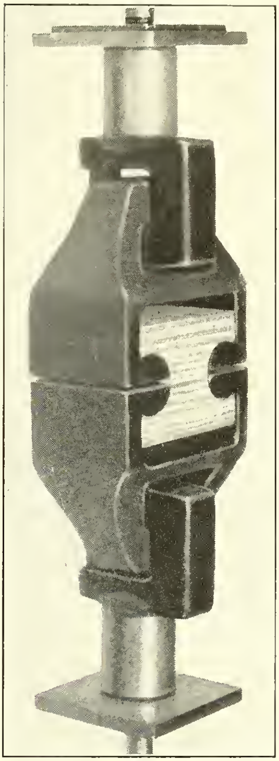
Sketching and Recording Data. A sketch is made of the end of the test specimen to show the character of the growth rings, and, after test, the failure is indicated for side and end surfaces. The actual dimensions of the shearing surface are measured and recorded on suitable data and computation cards, together with data on number of rings per inch, percent of sapwood and of summerwood, and moisture content.[21] The portion of the test piece which is sheared off is used for the moisture determination. The type of test, that is, whether tangential shear or radial shear, should be indicated.

---

[21] See Standard methods of testing small clear specimens of timber, footnote 1, Fig. 40 of Appendix, for sample data card.

Method. The test specimen is placed in the shear tool with the projecting lip under the sliding plate, which is centered under the crosshead of the testing machine. Care must be taken in placing the specimen to see that the cross bar of the shear tool is adjusted so that the edges of the specimen are vertical and the end rests evenly on the support over the contact area. The load is applied continuously throughout the test at a rate of 0.015 inch per minute. The maximum load only is observed. In all cases where the failure at the base of the specimen extends back onto the supporting surface, the test is culled.

Results. The shearing strength per square inch is found by dividing the maximum load by the shearing area ($Q = P/A$).



Yale Photo

FIG. 84. Tool for tension-perpendicular-to-the-grain test.

Tension Perpendicular to Grain

Apparatus. A universal testing machine and a pair of special testing grips are required. The latter are essentially double hooks or clamps, one of which is attached to the fixed crosshead, the other to the movable head (see Fig. 84).

Preparing the Material. Clear straight-grained specimens are cut, after being bored as described in the following paragraphs, to 2 by 2 by 2½ inches, the longest dimension being with the grain. At each end a 1-inch hole is bored with its center equidistant from the two sides and ¼ inch from the ends, thus making the area to be tested 1 by 2 inches (see Fig. 86*C*). Part of the specimens are cut so that the section of failure will be parallel to the growth rings (tangential); the balance at right angles to the growth rings (radial).

Sketching and Recording Data. Sketches and data similar to those specified for shear parallel to grain are made and entered on data and computation cards.[22] The actual width and length at the minimum section are measured. The moisture content is determined from one of the pieces remaining after failure or from a section split along the surface of failure.

Method. The free ends of the grips are fitted into the notches in the ends of the test specimen. The movable head of the machine is then made to descend (or ascend) at the rate of 0.10 inch per minute, pulling the specimen in two at right angles to the grain. The maximum load only is observed.

Results. The strength in tension perpendicular to the grain, in pounds per square inch, is found by dividing the observed maximum load by the actual area of the minimum section.

Cleavage

Apparatus. A static testing machine and a special cleavage testing device are required. The latter consists essentially of two grips or hooks, one of which is suspended from the center of the top of the cage, and the other extended above the lower crosshead (see Fig. 85).

Preparing the Material. Clear straight-grained specimens are cut to a nominal size of 2 by 2 by 3¾ inches, with the longest dimension extending with the grain. Prior to cutting to length, a 1-inch hole is bored at one end, with its center equidistant from the two sides and 0.25 inch from the end, making the section to be tested 2 by 3 inches (see Fig. 86*D*). The blocks are cut so that the section of failure will be tangential in part of them and radial in the others.

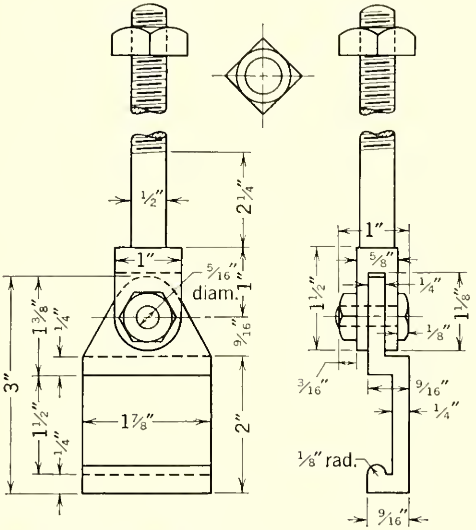
Sketching and Recording Data. The same procedure is followed as for tension perpendicular to grain tests (see Standard methods of testing small clear specimens of timber,[1] Fig. 42 of Appendix, for data and computation card).

Method. The free ends of the grips are fitted into the notch in the end of the test specimen. The movable head of the machine is then made to descend (or ascend) at the rate of 0.10 inch per minute, pulling the grips apart and splitting the block. The maximum load only is observed.

---

[22] See Standard methods of testing small clear specimens of timber, footnote 1, Fig. 41 of Appendix, for sample data card.

Results. Cleavage strength, in pounds per inch of width, is computed by dividing the observed maximum load by the actual width of the section at the point of application of stress.



Note - Two pieces included in one set:
One piece with shank 8" long.
One piece with shank 5½" long.

FIG. 85. Detail of grips used in cleavage testing device.

Tension Parallel to Grain

Apparatus. A universal testing machine, an extensometer, and a pair of special self-aligning and self-tightening grips are required. One of the grips is attached to the fixed crosshead and the other to the movable head.

Preparing the Material. Since the tensile strength of wood parallel to the grain is greater than the compressive strength, and much in excess of the shearing strength, it is very difficult to make satisfactory tests in tension parallel to the grain. In order to provide satisfactory gripping characteristics, the ends of the test specimen (which are subjected to both compression and shear) must be stronger than the minimum portion subjected to

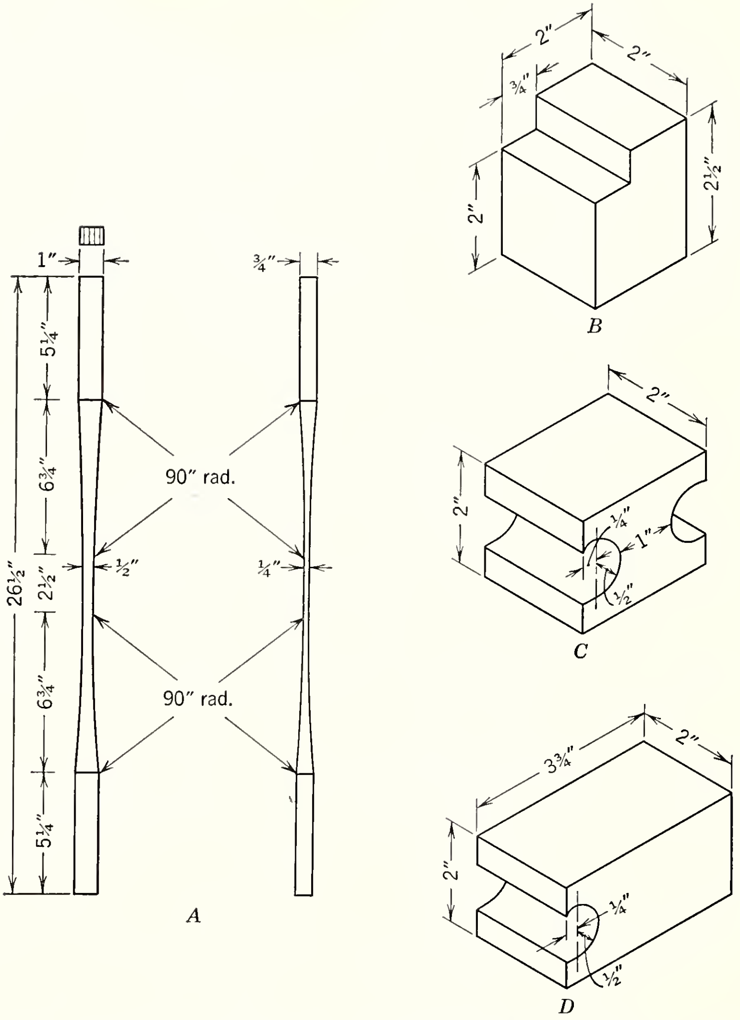

1"
¾"
5¼"
6¾"
2½"
26½"
6¾"
5¼"
90" rad.
½"
¼"
90" rad.
A
2"
¾"
2"
2"
2½"
B
2"
2"
¼"
1"
½"
C
3¾"
2"
2"
¼"
½"
D

Fig. 86. Details of test specimens. *A*. Tension parallel to grain. *B*. Shear. *C*. Tension perpendicular to grain. *D*. Cleavage.

pure tensile stress. Specimens of the size and shape shown in Fig. 86*A*, are recommended. All test pieces should be clear and straight grained. The growth rings are so oriented that, as seen on the cross section, they are perpendicular to the wide face of the specimen.

Sketching and Recording Data. Sketches are made of both ends of the test piece to show the character of the growth, and, after test, the failure is shown for all four sides. The actual cross-section dimensions at minimum section are measured to the nearest 0.001 inch. Data on rings per inch, percent of sapwood and of summerwood, and moisture content are recorded. The moisture determination is made on a sample 3 inches in length cut from the minimum section near the failure (see Standard methods of testing small clear specimens of timber,[1] Figs. 43–44 of Appendix, for sample log sheet and data and computation card).

Method. The test specimen is firmly fixed in grips of the type illustrated in Fig. 87. A dial-type extensometer is usually clamped to the specimen to permit determination of strain over a 2-inch central gage length as shown in Fig. 87. The movable head of the machine is set into motion at a uniform speed of 0.05 inch per minute until the specimen is pulled in two. Deformations are read to 0.0001 inch accuracy at uniform increments of load until the proportional limit has been passed. Loading is continued to failure, and maximum load is observed.

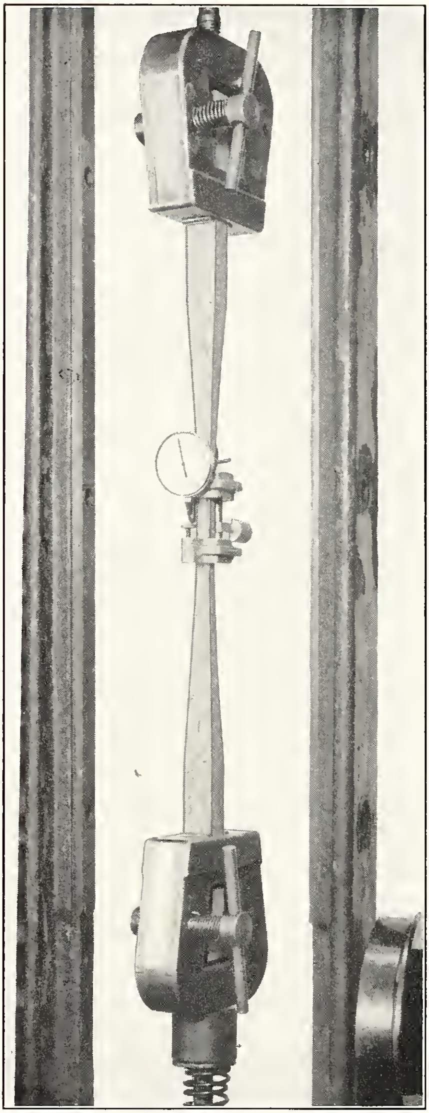
Results. Strength in tension parallel to the grain, in pounds per square inch, is computed by dividing the observed maximum load by the cross-section area at minimum section.

Toughness Test

Toughness, or the capacity of wood to absorb energy or resist shocks, is an important requirement in many uses of wood. Unfortunately, however, this property may be seriously affected by certain defects, such as minute compression failures or decay in its early stages of development, which are often indiscernible even under careful visual inspection. Consequently, for very exacting purposes, such as in aircraft construction, it is desirable to have some ready means of determining the toughness of representative samples of the wood intended for use.[23] To this

---

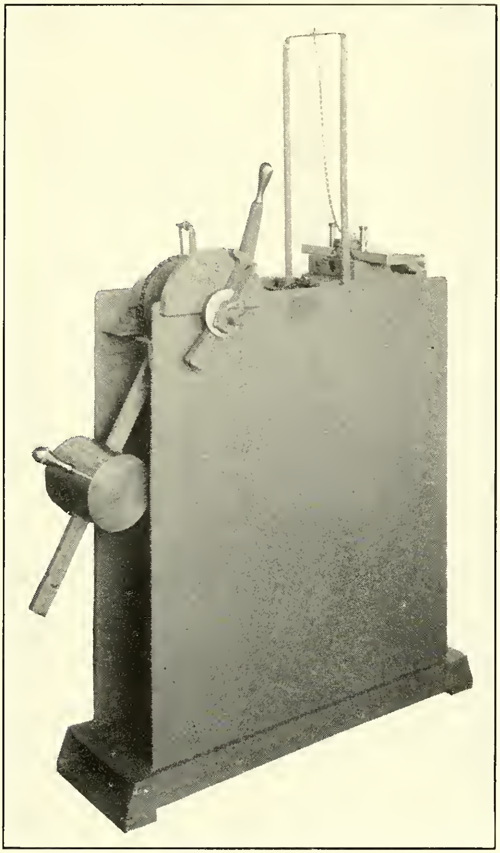
[23] Toughness may be determined from impact- and static-bending tests (in the latter case it is determined from values for work to maximum load and total work), but these methods are detailed and time-consuming and not adapted to general use as acceptance tests at woodworking establishments.



Forest Products Laboratory Photo Reproduced through Courtesy American Society for Testing Materials

FIG. 87. Test to determine strength of wood in tension parallel to the grain. Note self-aligning grips used to hold the specimens and use of extensometer to measure strain at the reduced section.

end the Forest Products Laboratory has designed the toughness machine and devised the method of test described in the following paragraphs.[24]



Southwark Division, Baldwin Locomotive Works, Photo

FIG. 88. Forest Products Laboratory toughness-testing machine showing initial position of pendulum, drum, and roller chain through which load is applied to the small specimen shown at the upper right.

The Forest Products Laboratory toughness-testing machine, one form of which is shown in Fig. 88, operates on the pendulum principle but differs radically from other types in that the load is applied to the specimen by means of a small yoke which is pulled by a roller-type steel chain fastened around a drum mounted on the axis of the pendulum, rather than by direct impact of pendulum or hammer on the specimen. If the pendulum is raised to some initial position and allowed to swing freely, it will reach a like height on the opposite side except for a small loss due to friction. When a specimen is in the machine, the pendulum fails to swing to a like height on the opposite side by an amount representing the energy consumed in breaking the piece. For any given setting of the machine, toughness is calculated from the final angle of swing.[25] The Forest Products Laboratory has prepared a table from which the toughness of the specimen can be read directly (see Table 26).

---

[24] From L. J. Markwardt, New toughness machine is aid in wood selection, *Wood Working Industries,* Jamestown, N.Y., Vol. 2, Jan. 1926, pp. 31–4.

See also *Forest Products Laboratory's toughness-testing machine,* For. Prod. Lab. Rept. 1308, Madison, 1941.

Arrangement is made for holding the pendulum in any one of three initial positions—30°, 45°, or 60° from the vertical—from which it is released for the test by a conveniently placed trip. The weight on the pendulum is, in addition, adjustable to four positions, so that specimens with a wide range of toughness may be provided for. The chain is slack when the pendulum is in the initial position. Its length is so adjusted that the pendulum applies the force when it swings to 15 degrees of the vertical, the object being to produce failure by the time the downward swing is completed. With very tough material earlier contact is provided, if necessary, to insure failure before the pendulum passes the vertical.

Standard toughness tests are made on specimens ⅝ by ⅝ by 10 inches in size, which are subjected to center loading over an 8-inch span. Load is applied through an aluminum tup of ¾-inch radius to the radial and to the tangential surfaces of alternate specimens. The initial angle of the pendulum and its position on the pendulum arm should be so selected in testing various woods that the difference between initial and final angle is not less than 10°.

The toughness-testing machine was originally developed to

---

[25] In calculating toughness, the following equation is used:

$$T = wl\ (\cos A_2 - \cos A_1)$$

in which T = toughness (work per specimen), inch-pounds; w = weight of pendulum, pounds; l = distance from supporting axis to center of pendulum, inches; A_1 = initial angle from vertical, degrees; A_2 = final angle, degrees.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*

Initial Angle 60° plus Friction

Final Angle. degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716		$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716
	In.-lb.						In.-lb.				
0.1	673.1	611.0	527.5	442.4	358.1	5.1	667.7	606.1	523.2	438.9	355.2
0.2	673.1	611.0	527.5	442.4	358.1	5.2	667.6	606.0	523.1	438.8	355.2
0.3	673.1	611.0	527.5	442.4	358.1	5.3	667.3	605.7	522.9	438.6	355.0
0.4	673.1	611.0	527.5	442.4	358.1	5.4	667.2	605.6	522.8	438.5	355.0
0.5	673.1	611.0	527.5	442.4	358.1	5.5	666.9	605.3	522.6	438.3	354.8
0.6	673.0	610.8	527.4	442.3	358.0	5.6	666.6	605.1	522.4	438.1	354.7
0.7	673.0	610.8	527.4	442.3	358.0	5.7	666.5	605.0	522.3	438.1	354.6
0.8	673.0	610.8	527.4	442.3	358.0	5.8	666.2	604.7	522.1	437.9	354.5
0.9	673.0	610.8	527.4	442.3	358.0	5.9	666.0	604.5	521.9	437.7	354.3
1.0	672.8	610.7	527.3	442.2	358.0	6.0	665.7	604.2	521.7	437.5	354.2
1.1	672.8	610.7	527.3	442.2	358.0	6.1	665.4	604.0	521.5	437.3	354.0
1.2	672.8	610.7	527.3	442.2	358.0	6.2	665.3	603.9	521.3	437.3	354.0
1.3	672.7	610.6	527.2	442.1	357.9	6.3	665.0	603.6	521.1	437.1	353.8
1.4	672.7	610.6	527.2	442.1	357.9	6.4	664.7	603.4	520.9	436.9	353.7
1.5	672.7	610.6	527.2	442.1	357.9	6.5	664.5	603.1	520.7	436.7	353.5
1.6	672.5	610.5	527.0	442.0	357.8	6.6	664.2	602.9	520.5	436.6	353.4
1.7	672.5	610.5	527.0	442.0	357.8	6.7	663.9	602.7	520.3	436.4	353.2
1.8	672.4	610.3	526.9	442.0	357.8	6.8	663.7	602.4	520.1	436.2	353.1
1.9	672.4	610.3	526.9	442.0	357.8	6.9	663.4	602.2	519.9	436.0	353.0
2.0	672.3	610.2	526.8	441.9	357.7	7.0	663.0	601.8	519.6	435.8	352.7
2.1	672.1	610.1	526.7	441.8	357.6	7.1	662.7	601.6	519.3	435.6	352.6
2.2	672.1	610.1	526.7	441.8	357.6	7.2	662.5	601.3	519.1	435.4	352.5
2.3	672.0	610.0	526.6	441.7	357.5	7.3	662.2	601.1	518.9	435.2	352.3
2.4	671.9	609.9	526.5	441.6	357.5	7.4	661.9	600.8	518.7	435.0	352.2
2.5	671.7	609.7	526.4	441.5	357.4	7.5	661.5	600.5	518.4	434.8	351.9
2.6	671.7	609.7	526.4	441.5	357.4	7.6	661.2	600.2	518.2	434.6	351.8
2.7	671.6	609.6	526.3	441.4	357.3	7.7	661.0	600.0	518.0	434.4	351.7
2.8	671.5	609.5	526.2	441.3	357.2	7.8	660.6	599.6	517.7	434.2	351.4
2.9	671.3	609.4	526.1	441.2	357.2	7.9	660.3	599.4	517.4	434.0	351.3
3.0	671.2	609.2	526.0	441.2	357.1	8.0	660.0	599.1	517.2	433.8	351.2
3.1	671.1	609.1	525.9	441.1	357.0	8.1	659.5	598.7	516.9	433.5	350.9
3.2	670.9	609.0	525.8	441.0	357.0	8.2	659.4	598.5	516.7	433.4	350.8
3.3	670.8	608.9	525.7	440.9	356.9	8.3	659.0	598.1	516.4	433.1	350.6
3.4	670.7	608.8	525.6	440.8	356.8	8.4	658.7	597.9	516.2	432.9	350.4
3.5	670.5	608.6	525.5	440.7	356.7	8.5	658.3	597.5	515.9	432.7	350.2
3.6	670.4	608.5	525.4	440.6	356.7	8.6	658.0	597.3	515.7	432.5	350.1
3.7	670.3	608.4	525.3	440.5	356.6	8.7	657.6	596.9	515.3	432.2	349.9
3.8	670.1	608.3	525.1	440.4	356.5	8.8	657.2	596.5	515.0	432.0	349.7
3.9	670.0	608.2	525.0	440.4	356.5	8.9	656.9	596.3	514.8	431.8	349.5
4.0	669.9	608.0	524.9	440.3	356.4	9.0	656.5	595.9	514.5	431.5	349.3
4.1	669.6	607.8	524.7	440.1	356.2	9.1	656.1	595.6	514.2	431.2	349.1
4.2	669.5	607.7	524.6	440.0	356.2	9.2	655.7	595.2	513.9	431.0	348.9
4.3	669.3	607.5	524.5	440.0	356.1	9.3	655.5	595.0	513.6	430.8	348.7
4.4	669.2	607.4	524.4	439.8	356.0	9.4	655.0	594.6	513.3	430.5	348.5
4.5	668.9	607.2	524.2	439.6	355.9	9.5	654.6	594.2	513.0	430.3	348.3
4.6	668.8	607.1	524.1	439.6	355.8	9.6	654.2	593.9	512.7	430.0	348.1
4.7	668.5	606.8	523.9	439.4	355.7	9.7	653.8	593.5	512.4	429.7	347.9
4.8	668.4	606.7	523.8	439.3	355.6	9.8	653.4	593.1	512.1	429.5	347.7
4.9	668.1	606.4	523.6	439.1	355.5	9.9	653.0	592.8	511.7	429.2	347.4
5.0	688.0	606.3	523.5	439.0	355.4	10.0	652.6	592.4	511.4	428.9	347.2

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 60° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716		$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716
	In.-lb.						In.-lb.				
10.1	652.2	592.0	511.1	428.7	347.0	15.1	626.6	568.8	491.1	411.9	333.4
10.2	651.8	591.7	510.8	428.4	346.8	15.2	626.0	568.2	490.5	411.4	333.0
10.3	651.4	591.3	510.5	428.1	346.6	15.3	625.4	567.7	490.1	411.1	332.8
10.4	651.0	590.9	510.2	427.9	346.4	15.4	624.8	567.1	489.6	410.6	332.4
10.5	650.6	590.6	509.9	427.6	346.1	15.5	624.1	566.5	489.1	410.2	332.0
10.6	650.1	590.1	509.4	427.3	345.9	15.6	623.5	566.0	488.6	409.8	331.8
10.7	649.7	589.7	509.1	427.0	345.6	15.7	622.9	565.4	488.1	409.4	331.4
10.8	649.3	589.3	508.8	426.7	345.4	15.8	622.2	564.8	487.6	408.9	331.0
10.9	648.9	589.0	508.5	426.5	345.2	15.9	621.5	564.2	487.1	408.5	330.7
11.0	648.3	588.5	508.1	426.1	344.9	16.0	621.0	563.7	486.6	408.2	330.4
11.1	647.9	588.1	507.7	425.8	344.7	16.1	620.3	563.1	486.1	407.7	330.0
11.2	647.5	587.7	507.4	425.6	344.5	16.2	619.6	562.4	485.6	407.3	329.7
11.3	647.0	587.3	507.0	425.2	344.2	16.3	619.0	561.8	485.1	406.8	329.3
11.4	646.6	586.9	506.7	425.0	344.0	16.4	618.3	561.2	484.5	406.4	329.0
11.5	646.0	586.4	506.3	424.6	343.7	16.5	617.6	560.6	484.0	405.9	328.6
11.6	645.6	586.0	505.9	424.3	343.5	16.6	617.0	560.0	483.5	405.5	328.2
11.7	645.1	585.5	505.5	424.0	343.2	16.7	616.3	559.4	482.9	405.1	327.9
11.8	644.7	585.2	505.2	423.7	343.0	16.8	615.6	558.8	482.4	404.6	327.5
11.9	644.1	584.7	504.8	423.4	342.7	16.9	614.9	558.2	481.9	404.2	327.2
12.0	643.6	584.2	504.4	423.0	342.4	17.0	614.3	557.6	481.4	403.7	326.8
12.1	643.2	583.8	504.0	422.8	542.2	17.1	613.6	557.0	480.8	403.3	326.5
12.2	642.7	583.3	503.6	422.4	341.9	17.2	612.9	556.3	480.3	402.8	326.1
12.3	642.1	582.9	503.2	422.0	341.6	17.3	612.2	555.7	479.8	402.4	325.7
12.4	641.7	582.5	502.9	421.8	341.4	17.4	611.4	555.0	479.2	401.9	325.3
12.5	641.2	582.0	502.5	421.4	341.1	17.5	610.8	554.4	478.6	401.4	324.9
12.6	640.6	581.5	502.0	421.1	340.8	17.6	610.1	553.8	478.1	401.0	324.6
12.7	640.1	581.0	501.6	420.7	340.6	17.7	609.4	553.2	477.6	400.5	324.2
12.8	639.6	580.5	501.2	420.4	340.3	17.8	608.6	552.4	476.9	400.0	323.8
12.9	639.2	580.2	500.9	420.1	340.1	17.9	607.9	551.8	476.4	399.6	323.4
13.0	638.6	579.7	500.5	419.7	339.8	18.0	607.3	551.2	475.9	399.1	323.1
13.1	638.1	579.2	500.0	419.4	339.5	18.1	606.5	550.5	475.2	398.6	322.7
13.2	637.5	578.7	499.6	419.0	339.2	18.2	605.8	549.9	474.7	398.2	322.3
13.3	637.0	578.2	499.2	418.7	338.9	18.3	605.0	549.1	474.1	397.6	321.9
13.4	636.5	577.8	498.8	418.3	338.6	18.4	604.3	548.5	473.6	397.2	321.5
13.5	635.9	577.2	498.4	418.0	338.3	18.5	603.5	547.8	472.9	396.6	321.1
13.6	635.4	576.7	497.9	417.6	338.1	18.6	602.8	547.2	472.4	396.2	320.7
13.7	634.7	576.1	497.4	417.2	337.7	18.7	602.0	546.4	471.8	395.7	320.3
13.8	634.2	575.6	497.0	416.8	337.4	18.8	601.2	545.7	471.1	395.1	319.9
13.9	633.6	575.2	496.6	416.5	337.1	18.9	600.5	545.1	470.6	394.7	319.5
14.0	633.1	574.7	496.1	416.1	336.8	19.0	599.7	544.4	470.0	394.2	319.1
14.1	632.6	574.2	495.7	415.8	336.6	19.1	598.9	543.6	469.3	393.6	318.6
14.2	631.9	573.6	495.2	415.3	336.2	19.2	598.2	543.0	468.8	393.2	318.3
14.3	631.4	573.1	494.8	415.0	335.9	19.3	597.4	542.3	468.2	392.7	317.9
14.4	630.8	572.6	494.3	414.6	335.6	19.4	596.6	541.6	467.5	392.1	317.4
14.5	630.1	572.0	493.8	414.2	335.3	19.5	595.8	540.8	466.9	391.6	317.0
14.6	629.6	571.5	493.4	413.8	335.0	19.6	595.1	540.2	466.4	391.2	316.6
14.7	629.1	571.0	493.0	413.5	334.7	19.7	594.3	539.5	465.8	390.6	316.2
14.8	628.4	570.4	492.4	413.0	334.3	19.8	593.5	538.7	465.1	390.1	315.8
14.9	627.9	569.9	492.0	412.7	334.0	19.9	592.7	538.0	464.5	389.6	315.4
15.0	627.2	569.3	491.5	412.2	333.7	20.0	591.9	537.3	463.9	389.0	314.9

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 60° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	wl = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716		*wl* = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716
	In.-lb.						In.-lb.				
20.1	591.1	536.5	463.2	388.5	314.5	25.1	546.0	495.6	427.9	358.9	290.5
20.2	590.3	535.8	462.6	388.0	314.1	25.2	544.9	494.6	427.0	358.2	289.9
20.3	589.5	535.1	462.0	387.4	313.6	25.3	544.0	493.8	426.3	357.5	289.4
20.4	588.7	534.3	461.3	386.9	313.2	25.4	542.9	492.8	425.5	356.8	288.9
20.5	587.9	533.6	460.7	386.4	312.8	25.5	542.0	492.3	424.7	356.2	288.3
20.6	587.1	532.9	460.1	385.9	312.3	25.6	540.9	491.0	423.9	355.5	287.8
20.7	586.1	532.0	459.3	385.2	311.8	25.7	539.9	490.1	423.1	354.9	287.3
20.8	585.3	531.3	458.7	384.7	311.4	25.8	538.9	489.1	422.3	354.2	286.7
20.9	584.5	530.6	458.1	384.2	311.0	25.9	537.9	488.3	421.6	353.6	286.2
21.0	583.7	529.8	457.4	383.6	310.6	26.0	536.9	487.3	420.7	352.9	285.6
21.1	582.9	529.1	456.8	383.1	310.1	26.1	535.8	486.3	419.9	352.1	285.1
21.2	581.9	528.2	456.0	382.5	309.6	26.2	534.8	485.5	419.1	351.5	284.6
21.3	581.1	527.5	455.4	382.0	309.2	26.3	533.8	484.5	418.3	350.8	284.0
21.4	580.3	526.8	454.8	381.4	308.8	26.4	532.7	483.5	417.4	350.1	283.4
21.5	579.4	525.9	454.0	380.8	308.3	26.5	531.6	482.5	416.6	349.4	282.8
21.6	578.6	525.2	453.4	380.3	307.8	26.6	530.7	481.7	415.9	348.8	282.3
21.7	577.6	524.3	452.7	379.7	307.3	26.7	529.6	480.7	415.0	348.1	281.8
21.8	576.8	523.6	452.0	379.1	306.9	26.8	528.5	479.7	414.2	347.4	281.2
21.9	575.9	522.7	451.3	378.5	306.4	26.9	527.4	478.7	413.3	346.7	280.6
22.0	575.1	522.0	450.7	378.0	306.0	27.0	526.4	477.8	412.5	346.0	280.0
22.1	574.1	521.1	449.9	377.4	305.5	27.1	525.3	476.8	411.6	345.2	279.5
22.2	573.3	520.4	449.3	376.8	305.0	27.2	524.2	475.8	410.8	344.5	278.9
22.3	572.4	519.6	448.6	376.2	304.5	27.3	523.1	474.8	409.9	343.8	278.3
22.4	571.4	518.7	447.8	375.6	304.0	27.4	522.0	473.9	409.1	343.1	277.7
22.5	570.6	518.0	447.2	375.1	303.6	27.5	521.0	472.9	408.3	342.4	277.2
22.6	569.7	517.1	446.4	374.4	303.1	27.6	519.9	471.9	407.4	341.7	276.6
22.7	568.8	516.3	445.7	373.8	302.6	27.7	518.8	470.9	406.6	341.0	276.0
22.8	567.9	515.5	445.1	373.3	302.2	27.8	517.7	470.0	405.7	340.3	275.5
22.9	567.0	514.7	444.3	372.7	301.7	27.9	516.7	469.0	404.9	339.6	274.9
23.0	566.1	513.8	443.6	372.1	301.2	28.0	515.4	467.9	403.9	338.8	274.2
23.1	565.1	513.0	442.9	371.4	300.7	28.1	514.4	466.9	403.1	338.1	273.7
23.2	564.2	512.1	442.1	370.8	300.2	28.2	513.3	465.9	402.2	337.4	273.1
23.3	563.2	511.3	441.4	370.2	299.7	28.3	512.2	464.9	401.4	336.7	272.5
23.4	562.4	510.5	440.8	369.7	299.2	28.4	511.0	463.8	400.5	335.9	271.9
23.5	561.5	509.7	440.0	369.0	298.7	28.5	509.9	462.9	399.6	335.2	271.3
23.6	560.5	508.8	439.3	368.4	298.2	28.6	508.9	461.9	398.8	334.4	270.7
23.7	559.6	508.0	438.5	367.8	297.7	28.7	507.6	460.8	397.8	333.7	270.1
23.8	558.7	507.1	437.8	367.2	297.2	28.8	506.6	459.8	397.0	332.9	269.5
23.9	557.7	506.2	437.1	366.6	296.7	28.9	505.5	458.8	396.1	332.2	268.9
24.0	556.6	505.3	436.2	365.9	296.2	29.0	504.3	457.7	395.2	331.4	268.3
24.1	555.7	504.4	435.5	365.2	295.7	29.1	503.2	456.8	394.3	330.7	267.7
24.2	554.8	503.6	434.7	364.6	295.2	29.2	502.0	455.7	393.4	329.9	267.1
24.3	553.8	502.7	434.0	364.0	294.7	29.3	500.9	454.7	392.5	329.2	266.5
24.4	552.9	501.8	433.3	363.4	294.2	29.4	499.7	453.6	391.6	328.4	265.9
24.5	551.9	501.0	432.5	362.8	293.6	29.5	498.6	452.6	390.7	327.7	265.3
24.6	550.9	500.0	431.7	362.1	293.1	29.6	497.4	451.5	389.8	326.9	264.6
24.7	549.9	499.2	430.9	361.4	292.6	29.7	496.2	450.4	388.8	326.1	264.0
24.8	549.0	498.3	430.2	360.8	292.1	29.8	495.1	449.4	388.0	325.4	263.4
24.9	547.9	497.3	429.4	360.1	291.5	29.9	493.9	448.3	387.1	324.6	262.8
25.0	546.9	496.5	428.6	359.5	291.0	30.0	492.7	447.2	386.1	323.8	262.1

---

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 60° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	wl = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716		*wl* = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716
	In.-lb.						In.-lb.				
30.1	491.6	446.2	385.3	323.1	261.6	35.1	428.2	388.7	335.6	281.5	227.8
30.2	490.4	445.1	384.3	322.3	260.9	35.2	426.9	387.5	334.5	280.6	227.1
30.3	489.2	444.0	383.4	321.5	260.3	35.3	425.5	386.2	333.5	279.7	226.4
30.4	488.0	442.9	382.4	320.7	259.6	35.4	424.2	385.0	332.4	278.8	225.7
30.5	486.8	441.8	381.5	319.9	259.0	35.5	422.8	383.8	331.4	277.9	225.0
30.6	485.6	440.7	380.5	319.1	258.3	35.6	421.5	382.6	330.3	277.0	224.2
30.7	484.5	439.8	379.7	318.4	257.8	35.7	420.1	381.4	329.2	276.1	223.5
30.8	483.3	438.7	378.7	317.6	257.1	35.8	418.8	380.1	328.2	275.3	222.8
30.9	482.1	437.6	377.8	316.8	256.5	35.9	417.3	378.8	327.0	274.3	222.0
31.0	480.9	436.5	376.8	316.0	255.8	36.0	416.0	377.6	326.0	273.4	221.3
31.1	479.6	435.4	375.9	315.2	255.2	36.1	414.6	376.4	324.9	272.5	220.6
31.2	478.4	434.3	374.9	314.5	254.5	36.2	413.3	375.1	323.9	271.6	219.9
31.3	477.2	433.2	374.0	313.7	253.9	36.3	411.8	373.8	322.7	270.7	219.1
31.4	476.0	432.1	373.0	312.9	253.3	36.4	410.4	372.6	321.7	269.8	218.4
31.5	474.7	430.8	372.0	312.0	252.5	36.5	409.1	371.3	320.6	268.9	217.7
31.6	473.4	429.7	371.0	311.2	251.9	36.6	407.6	370.0	319.4	267.9	216.9
31.7	472.2	428.6	370.1	310.4	251.2	36.7	406.3	368.8	318.4	267.0	216.2
31.8	471.0	427.6	369.1	309.6	250.6	36.8	404.8	367.4	317.2	266.1	215.4
31.9	469.8	426.4	368.2	308.8	250.0	36.9	403.4	366.2	316.2	265.2	214.7
32.0	468.5	425.2	367.1	307.9	249.2	37.0	402.0	364.9	315.0	264.2	213.9
32.1	467.3	424.1	366.2	307.1	248.6	37.1	400.6	363.6	313.9	263.3	213.1
32.2	466.0	423.0	365.2	306.3	248.0	37.2	399.1	362.3	312.8	262.3	212.4
32.3	464.8	421.9	364.3	305.5	247.3	37.3	397.8	361.1	311.7	261.5	211.6
32.4	463.5	420.7	363.2	304.6	246.6	37.4	396.3	359.7	310.6	260.5	210.9
32.5	462.3	419.6	362.3	303.8	245.9	37.5	395.0	358.5	309.5	259.6	210.1
32.6	461.1	418.5	361.3	303.0	245.3	37.6	393.5	357.2	308.4	258.6	209.4
32.7	459.7	417.3	360.3	302.2	244.6	37.7	392.0	355.8	307.2	257.6	208.6
32.8	458.5	416.2	359.3	301.4	243.9	37.8	390.7	354.6	306.1	256.8	207.8
32.9	457.2	415.0	358.3	300.5	243.2	37.9	389.2	353.3	305.0	255.8	207.1
33.0	455.9	413.9	357.3	299.7	242.6	38.0	387.7	351.9	303.8	254.8	206.3
33.1	454.6	412.6	356.3	298.8	241.9	38.1	386.2	350.6	302.7	253.8	205.5
33.2	453.4	411.5	355.3	298.0	241.2	38.2	384.9	349.3	301.6	253.0	204.8
33.3	452.0	410.3	354.2	297.1	240.5	38.3	383.4	348.0	300.4	252.0	204.0
33.4	450.7	409.1	353.2	296.2	239.8	38.4	381.9	346.7	299.3	251.0	203.2
33.5	449.5	408.0	352.2	295.4	239.1	38.5	380.4	345.3	298.1	250.0	202.4
33.6	448.1	406.9	351.2	294.5	238.4	38.6	378.9	344.0	297.0	249.1	201.6
33.7	446.9	405.7	350.2	293.7	237.8	38.7	377.5	342.6	295.8	248.1	200.8
33.8	445.6	404.5	349.2	292.9	237.1	38.8	376.0	341.3	294.6	247.1	200.0
33.9	444.2	403.2	348.1	292.0	236.4	38.9	374.5	339.9	293.5	246.1	199.3
34.0	442.9	402.0	347.1	291.1	235.6	39.0	373.0	338.6	292.3	245.2	198.5
34.1	441.7	400.9	346.1	290.3	235.0	39.1	371.5	337.3	291.2	244.2	197.7
34.2	440.3	399.7	345.1	289.4	234.3	39.2	370.1	335.9	290.0	243.2	196.9
34.3	439.0	398.5	344.0	288.5	233.6	39.3	368.6	334.6	288.8	242.3	196.1
34.4	437.6	397.2	343.0	287.6	232.8	39.4	367.1	333.2	287.7	241.3	195.3
34.5	436.3	396.0	341.9	286.8	232.1	39.5	365.6	331.9	286.5	240.3	194.5
34.6	434.9	394.8	340.8	285.9	231.4	39.6	364.1	330.5	285.4	239.3	193.7
34.7	433.6	393.6	339.8	285.0	230.7	39.7	362.7	329.2	284.2	238.4	192.9
34.8	432.3	392.4	338.7	284.1	230.0	39.8	361.2	327.8	283.0	237.4	192.2
34.9	431.0	391.3	337.8	283.3	229.3	39.9	359.7	326.5	281.9	236.4	191.4
35.0	429.7	390.0	336.7	282.4	228.6	40.0	358.1	325.0	280.6	235.4	190.5

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 60° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	wl = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716		*wl* = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716
	In.-lb.						In.-lb.				
40.1	356.6	323.7	279.5	234.4	189.7	45.1	277.2	251.6	217.2	182.2	147.5
40.2	355.1	322.3	278.3	233.4	188.9	45.2	275.4	250.0	215.8	181.0	146.5
40.3	353.6	321.0	277.1	232.4	188.2	45.3	273.8	248.5	214.6	180.0	145.7
40.4	352.0	319.5	275.9	231.4	187.3	45.4	272.2	247.1	213.3	178.9	144.8
40.5	350.5	318.2	274.7	230.4	186.5	45.5	270.4	245.5	211.9	177.8	143.9
40.6	349.1	316.8	273.5	229.4	185.7	45.6	268.8	244.0	210.7	176.7	143.0
40.7	347.4	315.4	272.3	228.4	184.9	45.7	267.1	242.4	209.3	175.5	142.1
40.8	346.0	314.0	271.1	227.4	184.1	45.8	265.5	241.0	208.0	174.5	141.2
40.9	344.5	312.7	270.0	226.4	183.3	45.9	263.8	239.4	206.7	173.3	140.3
41.0	342.9	311.2	268.7	225.4	182.4	46.0	262.1	237.9	205.4	172.3	139.4
41.1	341.4	309.9	267.5	224.4	181.6	46.1	260.3	236.3	204.0	171.1	138.5
41.2	339.8	308.4	266.3	223.3	180.8	46.2	258.6	234.7	202.7	170.0	137.6
41.3	338.3	307.1	265.1	222.3	180.0	46.3	257.0	233.3	201.4	168.9	136.7
41.4	336.7	305.6	263.8	221.3	179.1	46.4	255.2	231.7	200.0	167.8	135.8
41.5	335.2	304.3	262.7	220.3	178.3	46.5	253.6	230.2	198.7	166.7	134.9
41.6	333.6	302.8	261.4	219.2	177.5	46.6	251.9	228.6	197.4	165.5	134.0
41.7	332.0	301.3	260.1	218.2	176.6	46.7	250.1	227.0	196.0	164.4	133.1
41.8	330.5	300.0	259.0	217.2	175.8	46.8	248.4	225.4	194.6	163.2	132.1
41.9	328.9	298.5	257.7	216.2	175.0	46.9	246.8	224.0	193.4	162.2	131.3
42.0	327.3	297.0	256.5	215.1	174.1	47.0	245.0	222.4	192.0	161.0	130.4
42.1	325.8	295.7	255.3	214.1	173.3	47.1	243.3	220.8	190.6	159.9	129.4
42.2	324.2	294.2	254.0	213.1	172.5	47.2	241.5	219.2	189.3	158.7	128.5
42.3	322.5	292.8	252.8	212.0	171.6	47.3	239.9	217.7	188.0	157.7	127.6
42.4	321.1	291.4	251.6	211.0	170.8	47.4	238.1	216.2	186.6	156.5	126.7
42.5	319.4	290.0	250.3	210.0	170.0	47.5	236.4	214.6	185.2	155.4	125.8
42.6	317.8	288.5	249.1	208.9	169.1	47.6	234.6	213.0	183.9	154.2	124.8
42.7	316.2	287.0	247.8	207.8	168.2	47.7	232.9	211.4	182.5	153.1	123.9
42.8	314.6	285.6	246.5	206.8	167.4	47.8	231.1	209.8	181.1	151.9	123.0
42.9	313.0	284.1	245.3	205.7	166.5	47.9	229.4	208.2	179.8	150.8	122.0
43.0	311.5	282.8	244.1	204.7	165.7	48.0	227.6	206.6	178.4	149.6	121.1
43.1	309.9	281.3	242.8	203.7	164.9	48.1	225.9	205.0	177.0	148.5	120.2
43.2	308.3	279.8	241.6	202.6	164.0	48.2	224.1	203.4	175.6	147.3	119.3
43.3	306.7	278.4	240.3	201.6	163.2	48.3	222.4	201.9	174.3	146.2	118.3
43.4	305.0	276.9	239.0	200.5	162.3	48.4	220.6	200.3	172.9	145.0	117.4
43.5	303.4	275.4	237.8	199.4	161.4	48.5	218.9	198.7	171.5	143.9	116.5
43.6	301.8	274.0	236.5	198.4	160.6	48.6	217.1	197.1	170.2	142.7	115.5
43.8	300.2	272.5	235.3	197.3	159.7	48.7	215.4	195.5	168.8	141.6	114.6
43.7	298.6	271.0	234.0	196.2	158.9	48.8	213.6	193.9	167.4	140.4	113.7
43.9	297.0	269.6	232.7	195.2	158.0	48.9	211.9	192.3	166.0	139.3	112.7
44.0	295.2	268.0	231.3	194.0	157.1	49.0	210.1	190.7	164.7	138.1	111.8
44.1	293.6	266.5	230.1	193.0	156.2	49.1	208.3	189.0	163.2	136.9	110.8
44.2	292.0	265.0	228.8	191.9	155.3	49.2	206.5	187.4	161.8	135.7	109.9
44.3	290.4	263.6	227.5	190.8	154.5	49.3	204.8	185.9	160.5	134.6	108.9
44.4	288.8	262.1	226.3	189.8	153.6	49.4	203.0	184.3	159.1	133.4	108.0
44.5	287.1	260.6	225.0	188.7	152.8	49.5	201.1	182.6	157.6	132.2	107.0
44.6	285.4	259.0	223.6	187.6	151.8	49.6	199.4	181.0	156.2	131.0	106.1
44.7	283.8	257.6	222.4	186.6	151.0	49.7	197.6	179.4	154.9	129.9	105.1
44.8	282.2	256.1	221.1	185.5	150.1	49.8	195.9	177.8	153.5	128.7	104.2
44.9	280.4	254.5	219.7	184.3	149.2	49.9	194.0	176.1	152.0	127.5	103.2
45.0	278.8	253.1	218.5	183.2	148.3	50.0	192.2	174.5	150.6	126.3	102.3

---

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 60° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	wl = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716		*wl* = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716
	In.-lb.						In.-lb.				
50.1	190.3	172.8	149.2	125.1	101.3	55.1	97.1	88.1	76.1	63.8	51.6
50.2	188.6	171.2	147.8	124.0	100.3	55.2	95.2	86.4	74.6	62.6	50.6
50.3	186.8	169.6	146.4	122.8	99.4	55.3	93.3	84.7	73 1	61.3	49.6
50.4	185.0	167.9	144.9	121.6	98.4	55.4	91.3	82.8	71.5	60.0	48.6
50.5	183.2	166.3	143.6	120.4	97.5	55.5	89.4	81.1	70.0	58.7	47.6
50.6	181.3	164.6	142.1	119.2	96.5	55.6	87.5	79.4	68.6	57.5	46.4
50.7	179.6	163.0	140.7	118.0	95.5	55.7	85.5	77.6	67.0	56.2	45.5
50.8	177.7	161.3	139.3	116.8	94.5	55.8	83.6	75.9	65.5	54.9	44.5
50.9	175.9	159.7	137.9	115.6	93.6	55.9	81.6	74.0	63.9	53.6	43.4
51.0	174.1	158.0	136.4	114.4	92.6	56.0	79.7	72.3	62.5	52.4	42.4
51.1	172.3	156.4	135.0	113.3	91.7	56.1	77.7	70.5	60.9	51.1	41.5
51.2	170.4	154.7	133.6	112.0	90.7	56.2	75.8	68.8	59.4	49.8	40.3
51.3	168.5	153.0	132.1	110.8	89.7	56.3	73.8	67.0	57.8	48.5	39.2
51.4	166.8	151.4	130.7	109.6	88.7	56.4	71.9	65.3	56.3	47.2	38.2
51.5	164.9	149.7	129.2	108.4	87.7	56.5	69.9	63.4	54.8	45.9	37.2
51.6	163.0	148.0	127.8	107.1	86.7	56.6	68.0	61.7	53.3	44.7	36.2
51.7	161.3	146.4	126.4	106.0	85.8	56.7	66.0	59.9	51.7	43.4	35.1
51.8	159.4	144.7	124.9	104.8	84.8	56.8	64.1	58.2	50.2	42.1	34.1
51.9	157.5	143.0	123.4	103.5	83.8	56.9	62.1	56.3	48.6	40.8	33.0
52.0	155.8	141.4	122.1	102.4	82.9	57.0	60.0	54.5	47.1	39.5	31.9
52.1	153.9	139.7	120.6	101.1	81.9	57.1	58.2	52.8	45.6	38.2	30.9
52.2	152.0	138.0	119.1	99.9	80.9	57.2	56.1	51.0	44.0	36.9	29.9
52.3	150.1	136.2	117.6	98.7	79.9	57.3	54.1	49.1	42.4	35.6	28.8
52.4	148.2	134.5	116.1	97.4	78.9	57.4	52.5	47.4	40.9	34.3	27.8
52.5	146.5	132.9	114.8	96.3	77.9	57.5	50.2	45.6	39.3	33.0	26.7
52.6	144.6	131.2	113.5	95.0	76.9	57.6	48.2	43.7	37.8	31.7	25.6
52.7	142.7	129.5	111.8	93.8	75.9	57.7	46.3	42.0	36.3	30.4	24.6
52.8	140.8	127.8	110.3	92.5	74.9	57.8	44.3	40.2	34.7	29.1	23.6
52.9	138.9	126.1	108.9	91.3	73.9	57.9	42.3	38.4	33.1	27.8	22.5
53.0	137.0	124.4	107.4	90.1	72.9	58.0	40.3	36.5	31.5	26.5	21.4
53.1	135.2	122.7	105.9	88.8	71.9	58.1	38.3	34.7	30.0	25.1	20.3
53.2	133.3	121.0	104.4	87.6	70.9	58.2	36.3	33.0	28.5	23.9	19.3
53.3	131.4	119.3	103.0	86.4	69.9	58.3	34.3	31.2	26.9	22.6	18.3
53.4	129.5	117.5	101.5	85.1	68.9	58.4	32.3	29.3	25.3	21.2	17.2
53.5	127.6	115.8	100.0	83.9	67.9	58.5	30.3	27.5	23.7	19.9	16.1
53.6	125.7	114.1	98.5	82.6	66.9	58.6	28.3	25.7	22.2	18.6	15.0
53.7	123.8	112.4	97.1	81.4	65.9	58.7	26.3	23.8	20.6	17.3	14.0
53.8	122.0	110.7	95.6	80.2	64.9	58.8	24.2	22.0	19.0	15.9	12.9
53.9	120.1	109.0	94.1	78.9	63.9	58.9	22.2	20.2	17.4	14.6	11.8
54.0	118.2	107.3	92.6	77.7	62.9	59.0	20.2	18.3	15.8	13.3	10.7
54.1	116.3	105.6	91.1	76.4	61.9	59.1	18.2	16.5	14.2	11.9	9.7
54.2	114.4	103.9	89.7	75.2	60.9	59.2	16.2	14.7	12.7	10.6	8.6
54.3	112.4	102.0	88.1	73.9	59 8	59.3	14.1	12.8	11.1	9.3	7.5
54.4	110.5	100.3	86.6	72.6	58.8	59.4	12.1	11.0	9.5	8.0	6.4
54.5	108.6	98.6	85.1	71.4	57.8	59.5	10.1	9.2	7.9	6.6	5.4
54.6	106.8	96.9	83.7	70.2	56.8	59.6	8.1	7.3	6.3	5.3	4.3
54.7	104.9	95.2	82.2	68.9	55.8	59.7	6.1	5.5	4.7	4.0	3.2
54.8	102.8	93.4	80.6	67.6	54.7	59.8	4.0	3.7	3.2	2.7	2.1
54.9	101.0	91.6	79.1	66.4	53.7	59.9	2.0	1.8	1.6	1.3	1.1
55.0	99.1	89.9	77.6	65.1	52.7	60.0	0.0	0.0	0.0	0.0	0.0

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 45° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	wl = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716		*wl* = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716
	In.-lb.						In.-lb.				
0.1	394.3	357.9	309.0	259.2	209.8	5.1	388.9	353.0	304.8	255.6	206.9
0.2	394.3	357.9	309.0	259.2	209.8	5.2	388.8	352.9	304.7	255.5	206.8
0.3	394.3	357.9	309.0	259.2	209.8	5.3	388.5	352.6	304.5	255.3	206.7
0.4	394.3	357.9	309.0	259.2	209.8	5.4	388.4	352.5	304.3	255.3	206.6
0.5	394.3	357.9	309.0	259.2	209.8	5.5	388.1	352.3	304.1	255.1	206.5
0.6	394.2	357.8	308.9	259.1	209.7	5.6	387.8	352.0	303.9	254.9	206.3
0.7	394.2	357.8	308.9	259.1	209.7	5.7	387.7	351.9	303.8	254.8	206.3
0.8	394.2	357.8	308.9	259.1	209.7	5.8	387.4	351.7	303.6	254.6	206.1
0.9	394.2	357.8	308.9	259.1	209.7	5.9	387.2	351.4	303.4	254.5	206.0
1.0	394.0	357.7	308.8	259.0	209.6	6.0	386.9	351.2	303.2	254.3	205.8
1.1	394.0	357.7	308.8	259.0	209.6	6.1	386.6	350.9	303.0	254.1	205.7
1.2	394.0	357.7	308.8	259.0	209.6	6.2	386.5	350.8	302.9	254.0	205.6
1.3	393.9	357.5	308.7	258.9	209.6	6.3	386.2	350.6	302.7	253.8	205.5
1.4	393.9	357.5	308.7	258.9	209.6	6.4	385.9	350.3	302.5	253.7	205.3
1.5	393.9	357.5	308.7	258.9	209.6	6.5	385.7	350.1	302.2	253.5	205.2
1.6	393.8	357.4	308.6	258.8	209.5	6.6	385.4	349.8	302.0	253.3	205.1
1.7	393.8	357.4	308.6	258.8	209.5	6.7	385.1	349.6	301.8	253.1	204.9
1.8	393.6	357.3	308.5	258.7	209.4	6.8	384.9	349.3	301.6	253.0	204.8
1.9	393.6	357.3	308.5	258.7	209.4	6.9	384.6	349.1	301.4	252.8	204.6
2.0	393.5	357.2	308.4	258.6	209.4	7.0	384.2	348.7	301.1	252.5	204.4
2.1	393.4	356.9	308.3	258.5	209.3	7.1	383.9	348.5	300.9	252.3	204.3
2.2	393.4	356.9	308.3	258.5	209.3	7.2	383.7	348.2	300.7	252.2	204.1
2.3	393.2	356.9	308.1	258.4	209.2	7.3	383.4	348.0	300.4	252.0	204.0
2.4	393.1	356.8	308.0	258.4	209.1	7.4	383.1	347.8	300.2	251.8	203.8
2.5	392.9	356.7	307.9	258.3	209.1	7.5	382.7	347.4	299.9	251.5	203.6
2.6	392.9	356.7	307.9	258.3	209.1	7.6	382.4	347.1	299.7	251.4	203.5
2.7	392.8	356.6	307.8	258.2	209.0	7.7	382.2	346.9	299.5	251.2	203.3
2.8	392.7	356.4	307.7	258.1	208.9	7.8	381.8	346.5	299.2	250.9	203.1
2.9	392.5	356.3	307.6	258.0	208.8	7.9	381.5	346.3	299.0	250.7	203.0
3.0	392.4	356.2	307.5	257.9	208.8	8.0	381.2	346.0	298.8	250.6	202.8
3.1	392.3	356.1	307.4	257.8	208.7	8.1	380.8	345.7	298.4	250.3	202.6
3.2	392.1	355.9	307.3	257.7	208.6	8.2	380.6	345.4	298.2	250.1	202.5
3.3	392.0	355.8	307.2	257.6	208.6	8.3	380.2	345.1	297.9	249.9	202.3
3.4	391.9	355.7	307.1	257.6	208.5	8.4	379.9	344.8	297.7	249.7	202.1
3.5	391.7	355.6	307.0	257.5	208.4	8.5	379.5	344.5	297.4	249.4	201.9
3.6	391.6	355.5	306.9	257.4	208.3	8.6	379.2	344.2	297.2	249.2	201.8
3.7	391.5	355.3	306.8	257.3	208.3	8.7	378.8	343.8	296.9	249.0	201.5
3.8	391.3	355.2	306.7	257.2	208.2	8.8	378.4	343.5	296.5	248.7	201.3
3.9	391.2	355.1	306.6	257.1	208.1	8.9	378.1	343.2	296.3	248.5	201.2
4.0	391.1	355.0	306.5	257.0	208.1	9.0	377.7	342.9	296.0	248.3	201.0
4.1	390.8	354.7	306.2	256.9	207.9	9.1	377.3	342.5	295.7	248.0	200.8
4.2	390.7	354.6	306.1	256.8	207.8	9.2	376.9	342.1	295.4	247.7	200.5
4.3	390.5	354.5	306.0	256.7	207.8	9.3	376.7	341.9	295.2	247.6	200.4
4.4	390.4	354.4	305.9	256.6	207.7	9.4	376.3	341.5	294.9	247.3	200.2
4.5	390.1	354.1	305.7	256.4	207.6	9.5	375.9	341.2	294.5	247.0	200.0
4.6	390.0	354.0	305.6	256.3	207.5	9.6	375.4	340.8	294.2	246.8	199.8
4.7	389.7	353.7	305.4	256.1	207.3	9.7	375.0	340.4	293.9	246.5	199.5
4.8	389.6	353.6	305.3	256.1	207.3	9.8	374.6	340.1	293.6	246.2	199.3
4.9	389.3	353.4	305.1	255.9	207.1	9.9	374.2	339.7	293.3	246.0	199.2
5.0	389.2	353.3	305.0	255.8	207.1	10.0	373.8	339.3	293.0	245.7	199.0

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 45° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	$wl = 1346$	$wl = 1222$	$wl = 1055$	$wl = 885$	$wl = 716$		$wl = 1346$	$wl = 1222$	$wl = 1055$	$wl = 885$	$wl = 716$
	In.-lb.						In.-lb.				
10.1	373.4	339.0	292.6	245.4	198.7	15.1	347.9	315.7	272.6	228.6	185.1
10.2	373.0	338.6	292.3	245.2	198.5	15.2	347.2	315.1	272.1	288.2	184.7
10.3	372.6	338.2	292.0	244.9	198.2	15.3	346.6	314.6	271.6	227.8	184.4
10.4	372.2	337.9	291.7	244.6	198.0	15.4	346.0	314.0	271.1	227.4	184.1
10.5	371.8	337.5	291.4	244.4	197.8	15.5	345.3	313.4	270.6	226.9	183.7
10.6	371.3	337.0	291.0	244.0	197.5	15.6	344.8	312.9	270.2	226.6	183.4
10.7	370.9	336.6	290.6	243.8	197.3	15.7	344.1	312.3	269.6	226.2	183.1
10.8	370.5	336.3	290.3	243.5	197.1	15.8	343.4	311.7	269.1	225.7	182.7
10.9	370.1	335.9	290.0	243.2	196.9	15.9	342.7	311.1	268.6	225.3	182.3
11.0	369.5	335.4	289.6	242.9	196.6	16.0	342.2	310.6	268.2	224.9	182.1
11.1	369.1	335.1	289.3	242.6	196.4	16.1	341.5	310.0	267.6	224.5	181.7
11.2	368.7	334.7	288.9	242.3	196.2	16.2	340.9	309.4	267.1	224.0	181.3
11.3	368.2	334.2	288.5	242.0	195.9	16.3	340.2	308.8	266.6	223.6	181.0
11.4	367.8	333.8	288.2	241.7	195.7	16.4	339.5	308.2	266.1	223.1	180.6
11.5	367.2	333.3	287.8	241.4	195.4	16.5	338.8	307.6	265.5	222.7	180.3
11.6	366.8	333.0	287.5	241.1	195.2	16.6	338.2	306.9	265.0	222.3	179.9
11.7	366.3	332.5	287.0	240.8	194.9	16.7	337.5	306.3	264.5	221.6	179.6
11.8	365.9	332.1	286.7	240.5	194.7	16.8	336.8	305.7	263.9	221.4	179.2
11.9	365.4	331.6	286.3	240.1	194.4	16.9	336.1	305.1	263.4	220.9	178.8
12.0	364.8	331.1	285.9	239.8	194.1	17.0	335.5	304.5	262.9	220.5	178.5
12.1	364.4	330.8	285.6	239.5	193.9	17.1	334.8	303.9	262.4	220.0	178.1
12.2	363.9	330.3	285.1	239.2	193.6	17.2	334.1	303.3	261.8	219.6	177.8
12.3	363.3	329.8	284.7	238.8	193.3	17.3	333.4	302.7	261.3	219.2	177.4
12.4	362.9	329.4	284.4	238.5	193.1	17.4	332.6	301.9	260.7	218.6	177.0
12.5	362.4	328.9	284.0	238.2	192.8	17.5	332.0	301.3	260.1	218.2	176.6
12.6	361.9	328.5	283.6	237.8	192.5	17.6	331.3	300.7	259.6	217.7	176.3
12.7	361.3	328.0	283.1	237.5	192.2	17.7	330.6	300.1	259.1	217.3	175.9
12.8	360.8	327.5	282.7	237.1	191.9	17.8	329.8	299.4	258.5	216.8	175.5
12.9	360.4	327.1	282.4	236.9	191.7	17.9	329.1	298.8	257.9	216.3	175.1
13.0	359.8	326.6	282.0	236.5	191.4	18.0	328.5	298.1	257.4	215.9	174.8
13.1	359.3	326.1	281.6	236.1	191.2	18.1	327.7	297.4	256.3	215.4	174.3
13.2	358.8	325.6	281.1	235.8	190.9	18.2	327.0	296.8	256.2	214.9	174.0
13.3	358.2	325.2	280.7	235.4	190.6	18.3	326.2	296.1	255.6	214.4	173.5
13.4	357.7	324.7	280.3	235.1	190.3	18.4	325.5	295.5	255.1	213.9	173.2
13.5	357.1	324.2	279.9	234.7	190.0	18.5	324.7	294.7	254.5	213.4	172.8
13.6	356.6	323.7	279.5	234.4	189.7	18.6	324.0	294.1	253.9	213.0	172.4
13.7	355.9	323.1	278.9	233.9	189.4	18.7	323.2	293.4	253.3	212.4	172.0
13.8	355.4	322.6	278.5	233.6	189.1	18.8	322.4	292.7	252.7	211.9	171.5
13.9	354.9	322.1	278.1	233.2	188.8	18.9	321.7	292.0	252.1	211.5	171.2
14.0	354.3	321.6	277.7	232.9	188.5	19.0	320.9	291.3	251.5	210.9	170.7
14.1	353.8	321.1	277.2	232.5	188.2	19.1	320.1	290.6	250.9	210.4	170.3
14.2	353.1	320.5	276.7	232.1	187.9	19.2	319.4	290.0	250.3	210.0	170.0
14.3	352.6	320.0	276.3	231.7	187.6	19.3	318.6	289.2	249.7	209.4	169.5
14.4	352.0	319.5	275.9	231.4	187.3	19.4	317.8	288.5	249.1	208.9	169.1
14.5	351.4	318.9	275.3	230.9	186.9	19.5	317.0	287.8	248.4	208.4	168.7
14.6	350.8	318.4	274.9	230.6	186.6	19.6	316.4	287.2	247.9	207.9	168.3
14.7	350.3	317.9	274.5	230.2	186.4	19.7	315.5	286.4	247.3	207.4	167.9
14.8	349.6	317.3	274.0	229.8	186.0	19.8	314.7	285.7	246.6	206.9	167.5
14.9	349.1	316.8	273.5	229.4	185.7	19.9	313.9	285.0	246.0	206.3	167.0
15.0	348.4	316.2	273.0	229.0	185.4	20.0	313.1	284.2	245.4	205.8	166.6

---

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 45° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716		$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716
	In.-lb.						In.-lb.				
20.1	312.3	283.5	244.7	205.3	166.2	25.1	267.2	242.6	209.4	175.6	142.2
20.2	311.5	282.8	244.1	204.7	165.7	25.2	266.1	241.6	206.4	174.9	141.6
20.3	310.7	282.0	243.5	204.2	165.3	25.3	265.2	240.7	207.8	174.3	141.1
20.4	309.9	281.3	242.8	203.7	164.9	25.4	264.1	239.7	207.0	173.6	140.5
20.5	309.1	280.6	242.2	203.1	164.4	25.5	263.2	238.9	206.2	173.0	140.0
20.6	308.5	279.8	241.6	202.6	164.0	25.6	262.1	237.9	205.4	172.3	139.4
20.7	307.3	279.0	240.8	202.0	163.5	25.7	261.2	237.1	204.7	171.6	138.9
20.8	306.5	278.2	240.2	201.5	163.1	25.8	260.1	236.1	203.8	170.9	138.4
20.9	305.7	277.5	239.6	200.9	162.7	25.9	259.1	235.2	203.1	170.3	137.9
21.0	304.9	276.8	238.9	200.4	162.2	26.0	258.1	234.2	202.2	169.6	137.3
21.1	304.1	276.0	238.3	199.9	161.8	26.1	257.0	233.3	201.4	168.9	136.7
21.2	303.2	275.2	237.6	199.3	161.3	26.2	256.0	232.4	200.6	168.3	136.2
21.3	302.4	274.4	236.9	198.7	160.9	26.3	255.0	231.4	199.8	167.6	135.7
21.4	301.5	273.7	236.3	198.2	160.4	26.4	253.9	230.5	199.0	166.9	135.1
21.5	300.6	272.9	235.6	197.6	159.9	26.5	252.8	229.5	198.1	166.2	134.5
21.6	299.8	272.1	234.9	197.0	159.5	26.6	251.9	228.6	197.4	165.5	134.0
21.7	298.8	271.3	234.2	196.4	159.0	26.7	250.8	227.6	196.5	164.8	133.4
21.8	298.0	270.5	233.6	195.9	158.6	26.8	249.7	226.7	195.7	164.1	132.9
21.9	297.1	269.7	232.8	195.3	158.1	26.9	248.6	225.7	194.8	163.4	132.3
22.0	296.3	268.9	232.2	194.7	157.6	27.0	247.6	224.7	194.0	162.7	131.7
22.1	295.4	268.1	231.5	194.1	157.1	27.1	246.5	223.7	193.2	162.0	131.1
22.2	294.5	267.4	230.8	193.6	156.7	27.2	245.4	222.8	192.3	161.3	130.6
22.3	293.6	266.5	230.1	193.0	156.2	27.3	244.3	221.8	191.5	160.6	130.0
22.4	292.7	265.6	229.3	192.3	155.7	27.4	243.3	220.8	190.6	159.9	129.4
22.5	291.8	264.9	228.7	191.8	155.3	27.5	242.2	219.8	189.8	159.2	128.8
22.6	290.9	264.1	228.0	191.2	154.8	27.6	241.1	218.8	188.9	158.5	128.3
22.7	290.0	263.2	227.2	190.6	154.3	27.7	240.0	217.9	188.1	157.8	127.7
22.8	289.2	262.5	226.6	190.1	153.8	27.8	238.9	216.9	187.3	157.0	127.1
22.9	288.2	261.6	225.9	189.4	153.3	27.9	237.9	215.9	186.4	156.3	126.6
23.0	287.3	260.8	225.1	189.0	152.8	28.0	236.7	214.8	185.5	155.5	125.9
23.1	286.3	259.9	224.4	188.2	152.3	28.1	235.6	213.8	184.6	154.8	125.3
23.2	285.4	259.0	223.6	187.6	151.8	28.2	234.5	212.9	183.8	154.1	124.8
23.3	284.4	258.2	222.9	187.0	151.3	28.3	233.4	211.9	182.9	152.4	124.2
23.4	283.6	257.5	222.3	186.4	150.9	28.4	232.2	210.8	182.0	152.6	123.5
23.5	282.7	256.6	221.5	185.8	150.4	28.5	231.1	209.8	181.1	151.9	123.0
23.6	281.8	255.7	220.8	185.2	149.9	28.6	230.1	208.8	180.3	151.2	122.4
23.7	280.8	254.9	220.1	184.6	149.4	28.7	228.8	207.7	179.3	150.4	121.8
23.8	279.9	254.0	219.3	183.9	148.9	28.8	227.8	206.7	178.5	149.7	121.2
23.9	278.9	253.2	218.6	183.3	148.4	28.9	226.7	205.8	177.7	149.0	120.6
24.0	277.8	252.2	217.7	182.6	147.8	29.0	225.5	204.7	176.7	148.2	120.0
24.1	276.9	251.3	217.0	182.0	147.3	29.1	224.4	203.7	175.9	147.5	119.4
24.2	276.0	250.5	216.3	181.4	146.8	29.2	223.2	202.6	174.9	146.7	118.7
24.3	275.0	249.6	215.5	180.8	146.3	29.3	222.1	201.6	174.1	146.0	118.2
24.4	274.1	248.8	214.8	180.1	145.8	29.4	220.9	200.5	175.1	145.2	117.5
24.5	273.1	247.9	214.0	179.5	145.3	29.5	219.8	199.5	172.3	144.5	117.0
24.6	272.1	247.0	213.2	178.8	144.7	29.6	218.6	198.4	171.3	143.8	116.2
24.7	271.1	246.1	212.5	178.2	144.2	29.7	217.4	197.3	170.4	142.9	115.7
24.8	270.2	245.2	211.7	177.6	143.7	29.8	216.3	196.4	169.5	142.2	115.1
24.9	269.1	244.3	210.9	176.9	143.2	29.9	215.1	195.3	168.6	141.4	114.5
25.0	268.2	243.4	210.1	176.2	142.7	30.0	213.9	194.2	167.6	140.6	113.8

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 45° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	wl = 1346	wl = 1222	wl = 1055	wl = 885	wl = 716		wl = 1346	wl = 1222	wl = 1055	wl = 885	wl = 716
	In.-lb.						In.-lb.				
30.1	212.8	193.2	166.8	139.9	113.2	35.1	149.4	135.6	117.1	98.2	79.5
30.2	211.6	192.1	165.8	139.1	112.6	35.2	148.1	134.4	116.0	97.3	78.7
30.3	210.4	191.0	164.9	138.3	111.9	35.3	146.7	133.2	115.0	96.4	78.1
30.4	209.2	189.9	163.9	137.5	111.3	35.4	145.4	132.0	113.9	95.6	77.4
30.5	208.0	188.8	163.0	136.7	110.7	35.5	144.0	130.7	112.9	94.7	76.6
30.6	206.8	187.7	162.0	135.9	110.0	35.6	142.7	129.5	111.8	93.8	75.9
30.7	205.7	186.7	161.2	135.2	109.4	35.7	141.3	128.3	110.8	92.9	75.2
30.8	204.5	185.6	160.2	134.4	108.8	35.8	140.0	127.1	109.7	92.0	74.5
30.9	203.3	184.5	159.3	133.6	108.1	35.9	138.5	125.7	108.6	91.0	73.7
31.0	202.1	183.4	158.3	132.8	107.5	36.0	137.2	124.5	107.5	90.2	73.0
31.1	200.8	182.3	157.4	132.0	106.9	36.1	135.8	123.3	106.4	89.3	72.3
31.2	199.6	181.2	156.4	131.2	106.2	36.2	134.5	122.1	105.4	88.4	71.6
31.3	198.4	180.1	155.5	130.4	105.6	36.3	133.0	120.7	104.2	87.4	70.8
31.4	197.2	179.0	154.5	129.6	104.9	36.4	131.7	119.5	103.2	86.5	70.0
31.5	195.9	177.8	153.5	128.7	104.2	36.5	130.3	118.3	102.1	85.6	69.3
31.6	194.7	176.7	152.5	127.9	103.6	36.6	128.8	116.9	101.0	84.7	68.5
31.7	193.4	175.6	151.6	127.1	102.9	36.7	127.5	115.7	99.9	83.8	67.8
31.8	192.2	174.5	150.6	126.3	102.3	36.8	126.0	114.4	98.7	82.8	67.0
31.9	191.0	173.4	149.7	125.6	101.6	36.9	124.7	113.1	97.7	81.9	66.3
32.0	189.7	172.2	148.6	124.7	100.9	37.0	123.2	111.8	96.5	81.0	65.5
32.1	188.5	171.1	147.7	123.9	100.3	37.1	121.8	110.6	95.5	80.1	64.8
32.2	187.3	170.0	146.7	123.1	99.6	37.2	120.3	109.2	94.3	79.1	64.0
32.3	186.0	168.9	145.8	122.3	99.0	37.3	119.0	108.0	93.3	78.2	63.3
32.4	184.7	167.6	144.7	121.4	98.3	37.4	117.5	106.7	92.1	77.2	62.5
32.5	183.5	166.5	143.8	120.6	97.6	37.5	116.2	105.5	91.0	76.4	61.8
32.6	182.3	165.4	142.8	119.8	97.0	37.6	114.7	104.1	89.9	75.4	61.0
32.7	180.9	164.2	141.8	118.9	96.3	37.7	113.2	102.8	88.7	74.4	60.2
32.8	179.7	163.1	140.8	118.1	95.6	37.8	111.9	101.5	87.7	73.5	59.5
32.9	178.4	161.9	139.8	117.2	94.9	37.9	110.4	100.2	86.5	72.6	58.7
33.0	177.2	160.8	138.8	116.4	94.3	38.0	108.9	98.9	85.3	71.6	57.9
33.1	175.8	159.6	137.8	115.6	93.5	38.1	107.4	97.5	84.2	70.6	57.2
33.2	174.6	158.5	136.8	114.8	92.9	38.2	106.1	96.3	83.1	69.7	56.4
33.3	173.3	157.3	135.8	113.9	92.2	38.3	104.6	94.9	82.0	68.7	55.7
33.4	171.9	156.0	134.7	113.0	91.5	38.4	103.1	93.6	80.8	67.8	54.9
33.5	170.7	154.9	133.8	112.2	90.8	38.5	101.6	92.3	79.6	66.8	54.1
33.6	169.3	153.7	132.7	111.3	90.1	38.6	100.2	90.9	78.5	65.8	53.3
33.7	168.1	152.6	131.8	110.5	89.5	38.7	98.7	89.6	77.3	64.9	52.5
33.8	166.8	151.4	130.7	109.6	88.7	38.8	97.2	88.2	76.2	63.9	51.7
33.9	165.4	150.2	129.7	108.7	88.0	38.9	95.7	86.9	75.0	62.9	50.9
34.0	164.1	149.0	128.6	107.9	87.3	39.0	94.2	85.5	73.8	61.9	50.1
34.1	162.9	147.9	127.6	107.1	86.7	39.1	92.8	84.2	72.7	61.0	49.3
34.2	161.5	146.6	126.6	106.2	85.9	39.2	91.3	82.8	71.5	60.0	48.6
34.3	160.2	145.4	125.5	105.3	85.2	39.3	89.8	81.5	70.4	59.0	47.8
34.4	158.8	144.2	124.5	104.4	84.5	39.4	88.3	80.2	69.2	58.0	47.0
34.5	157.5	143.0	123.4	103.5	83.8	39.5	86.8	78.8	68.0	57.1	46.2
34.6	156.2	141.7	122.4	102.6	83.1	39.6	85.3	77.5	66.9	56.1	45.4
34.7	154.8	140.5	121.3	101.8	82.4	39.7	83.9	76.1	65.7	55.1	44.6
34.8	153.5	139.3	120.3	100.9	81.6	39.8	82.4	74.8	64.6	54.1	43.8
34.9	152.3	138.2	119.3	100.1	81.0	39.9	80.9	73.4	63.4	53.2	43.0
35.0	150.9	137.0	118.3	99.2	80.3	40.0	79.3	72.0	62.1	52.1	42.2

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 45° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716		$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716
	In.-lb.						In.-lb.				
40.1	77.8	70.6	61.0	51.1	41.4	42.6	39.0	35.4	30.6	25.7	20.8
40.2	76.3	69.3	59.8	50.2	40.6	42.7	37.4	34.0	29.3	24.6	19.9
40.3	74.8	67.9	58.7	49.2	39.8	42.8	35.8	32.5	28.1	23.5	19.1
40.4	73.2	66.5	57.4	48.1	39.0	42.9	34.2	31.0	26.6	22.5	18.2
40.5	71.8	65.1	56.2	47.2	38.2	43.0	32.7	29.7	25.6	21.5	17.4
40.6	70.3	63.8	55.1	46.2	37.4	43.1	31.1	28.2	24.4	20.4	16.5
40.7	68.7	62.3	53.8	45.1	36.5	43.2	29.5	26.8	23.1	19.4	15.7
40.8	67.2	61.0	52.6	44.2	35.7	43.3	27.9	25.3	21.8	18.3	14.8
40.9	65.7	59.6	51.5	43.2	35.0	43.4	26.3	23.8	20.6	17.3	14.0
41.0	64.1	58.2	59.2	42.1	34.1	43.5	24.6	22.4	19.3	16.2	13.1
41.1	62.6	56.8	49.1	41.1	33.3	43.6	23.0	20.9	18.0	15.1	12.2
41.2	61.0	55.4	47.8	40.1	32.4	43.7	21.4	19.4	16.8	14.1	11.4
41.3	59.5	54.0	46.6	39.1	31.7	43.8	19.8	18.0	15.5	13.0	10.5
41.4	57.9	52.5	45.4	38.0	30.8	43.8	18.2	16.5	14.2	11.9	9.7
41.5	56.4	51.2	44.2	37.1	30.0	44.0	16.4	14.9	12.9	10.8	8.7
41.6	54.8	49.7	42.9	36.0	29.2	44.1	14.8	13.4	11.6	9.7	7.9
41.7	53.2	48.3	41.7	34.9	28.3	44.2	13.2	12.0	10.3	8.7	7.0
41.8	51.7	46.9	40.5	34.0	27.5	44.3	11.6	10.5	9.1	7.6	6.1
41.9	50.1	45.5	39.2	32.9	26.6	44.4	10.0	9.0	7.8	6.5	5.3
42.0	48.5	44.0	38.0	31.9	25.8	44.5	8.3	7.6	6.5	5.5	4.4
42.1	47.0	42.6	36.8	30.9	25.0	44.6	6.6	6.0	5.2	4.3	3.5
42.2	45.4	41.2	35.6	29.8	24.1	44.7	5.0	4.5	3.9	3.3	2.6
42.3	43.8	39.7	34.3	28.8	23.3	44.8	3.4	3.1	2.6	2.2	1.8
42.4	42.3	38.4	33.1	27.8	22.5	44.9	1.6	1.5	1.3	1.1	0.9
42.5	40.7	36.9	31.9	26.7	21.6	45.0	0.0	0.0	0.0	0.0	0.0

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

TABLE 26. CALCULATED TOUGHNESS VALUES FOR USE WITH FOREST PRODUCTS LABORATORY TOUGHNESS-TESTING MACHINE*—*Continued*

Initial Angle 30° plus Friction

Final Angle; degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	wl = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716		*wl* = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716
	In.-lb.						In.-lb.				
0.1	180.4	163.7	141.4	118.6	96.0	5.1	175.0	158.8	137.1	115.0	93.1
0.2	180.4	163.7	141.4	118.6	96.0	5.2	174.9	158.7	137.0	114.9	93.0
0.3	180.4	163.7	141.4	118.6	96.0	5.3	174.6	158.5	136.8	114.8	92.9
0.4	180.4	163.7	141.4	118.6	96.0	5.4	174.5	158.4	136.7	114.7	92.8
0.5	180.4	163.7	141.4	118.6	96.0	5.5	174.2	158.1	136.5	114.5	92.7
0.6	180.3	163.6	141.3	118.5	95.9	5.6	173.9	157.9	136.3	114.3	92.5
0.7	180.3	163.6	141.3	118.5	95.9	5.7	173.8	157.8	136.2	114.2	92.5
0.8	180.3	163.6	141.3	118.5	95.9	5.8	173.5	157.5	136.0	114.0	92.3
0.9	180.3	163.6	141.3	118.5	95.9	5.9	173.3	157.3	135.8	113.9	92.2
1.0	180.1	163.5	141.2	118.4	95.8	6.0	173.0	157.0	135.6	113.7	92.0
1.1	180.1	163.5	141.2	118.4	95.8	6.1	172.7	156.8	135.3	113.5	91.9
1.2	180.1	163.5	141.2	118.4	95.8	6.2	172.6	156.7	135.2	113.4	91.8
1.3	180.0	163.4	141.0	118.3	95.8	6.3	172.3	156.4	135.0	113.3	91.7
1.4	180.0	163.4	141.0	118.3	95.8	6.4	172.0	156.2	134.8	113.1	91.5
1.5	180.0	163.4	141.0	118.3	95.8	6.5	171.8	155.9	134.6	112.9	91.4
1.6	179.8	163.2	140.9	118.2	95.7	6.6	171.5	155.7	134.4	112.7	91.2
1.7	179.8	163.2	140.9	118.2	95.7	6.7	171.2	155.4	134.2	112.5	91.1
1.8	179.7	163.1	140.8	118.1	95.6	6.8	171.0	155.2	134.0	112.4	91.0
1.9	179.7	163.1	140.8	118.1	95.6	6.9	170.7	154.9	133.8	112.2	90.8
2.0	179.6	163.0	140.7	118.0	95.5	7.0	170.3	154.6	133.4	111.9	90.6
2.1	179.4	162.9	140.6	117.9	95.5	7.1	170.0	154.3	133.2	111.7	90.5
2.2	179.4	162.9	140.6	117.9	95.5	7.2	169.8	154.1	133.0	111.6	90.3
2.3	179.3	162.8	140.5	117.9	95.4	7.3	169.5	153.8	132.8	111.4	90.2
2.4	179.2	162.6	140.4	117.8	95.3	7.4	169.2	153.6	132.6	111.2	90.0
2.5	179.0	162.5	140.3	117.7	95.3	7.5	168.8	153.2	132.3	111.0	89.8
2.6	179.0	162.5	140.3	117.7	95.3	7.6	168.5	153.0	132.1	110.8	89.7
2.7	178.9	162.4	140.2	117.6	95.2	7.7	168.3	152.7	131.9	110.6	89.5
2.8	178.8	162.3	140.1	117.5	95.1	7.8	167.9	152.4	131.6	110.3	89.3
2.9	178.6	162.1	140.0	117.4	95.0	7.9	167.6	152.1	131.3	110.2	89.2
3.0	178.5	162.0	139.9	117.3	95.0	8.0	167.3	151.9	131.1	110.0	89.0
3.1	178.4	161.9	139.8	117.2	94.9	8.1	166.9	151.5	130.8	109.7	88.8
3.2	178.2	161.8	139.7	117.1	94.8	8.2	166.7	151.3	130.6	109.5	88.7
3.3	178.1	161.7	139.6	117.1	94.8	8.3	166.3	150.9	130.3	109.3	88.5
3.4	178.0	161.5	139.5	117.0	94.7	8.4	166.0	150.7	130.1	109.1	88.3
3.5	177.8	161.4	139.4	116.9	94.6	8.5	165.6	150.3	129.8	108.8	88.1
3.6	177.7	161.3	139.3	116.8	94.5	8.6	165.3	149.9	129.5	108.7	88.0
3.7	177.6	161.2	139.1	116.7	94.5	8.7	164.9	149.7	129.2	108.4	87.8
3.8	177.4	161.0	139.0	116.6	94.4	8.8	164.5	149.3	128.9	108.1	87.5
3.9	177.3	160.9	138.9	116.5	94.3	8.9	164.2	149.1	128.7	107.9	87.4
4.0	177.2	160.8	138.8	116.4	94.3	9.0	163.8	148.7	128.4	107.7	87.2
4.1	176.9	160.6	138.6	116.3	94.1	9.1	163.4	148.3	128.1	107.4	86.9
4.2	176.8	160.4	138.5	116.2	94.0	9.2	163.0	148.0	127.8	107.1	86.7
4.3	176.6	160.3	138.4	116.1	94.0	9.3	162.8	147.7	127.5	107.0	86.6
4.4	176.5	160.2	138.3	116.0	93.9	9.4	162.3	147.4	127.2	106.7	86.4
4.5	176.2	159.9	138.1	115.8	93.8	9.5	161.9	147.0	126.9	106.4	86.2
4.6	176.1	159.8	138.0	115.7	93.7	9.6	161.5	146.6	126.6	106.2	85.9
4.7	175.8	159.6	137.8	115.6	93.5	9.7	161.1	146.3	126.3	105.9	85.7
4.8	175.7	159.5	137.7	115.5	93.5	9.8	160.7	145.9	126.0	105.6	85.5
4.9	175.4	159.2	137.5	115.3	93.3	9.9	160.3	145.5	125.6	105.4	85.3
5.0	175.3	159.1	137.4	115.2	93.3	10.0	159.9	145.2	125.3	105.1	85.1

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308, 1941.

Table 26. Calculated Toughness Values for Use with Forest Products Laboratory Toughness-Testing Machine*—*Continued*

Initial Angle 30° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716		$wl =$ 1346	$wl =$ 1222	$wl =$ 1055	$wl =$ 885	$wl =$ 716
	In.-lb.						In.-lb.				
10.1	159.5	144.8	125.0	104.8	84.9	15.1	133.9	121.6	105.0	88.0	71.3
10.2	159.1	144.4	124.7	104.6	84.7	15.2	133.3	121.0	104.4	87.6	70.9
10.3	158.7	144.1	124.4	104.3	84.4	15.3	132.7	120.5	104.0	87.2	70.6
10.4	158.3	143.7	124.1	104.1	84.2	15.4	132.1	119.9	103.5	86.8	70.3
10.5	157.9	143.3	123.7	103.8	84.0	15.5	131.4	119.3	103.0	86.4	69.9
10.6	157.4	142.8	123.3	103.4	83.7	15.6	130.8	118.8	102.5	86.0	69.6
10.7	157.0	142.5	123.0	103.2	83.5	15.7	130.2	118.2	102.0	85.6	69.3
10.8	156.6	142.1	122.7	102.9	83.3	15.8	129.5	117.5	101.5	85.1	68.9
10.9	156.2	141.7	122.4	102.6	83.1	15.9	128.8	116.9	101.0	84.7	68.5
11.0	155.6	141.3	122.0	102.3	82.8	16.0	128.3	116.4	100.5	84.3	68.3
11.1	155.2	140.9	121.6	102.0	82.6	16.1	127.6	115.8	100.0	83.9	67.9
11.2	154.8	140.5	121.3	101.8	82.4	16.2	126.9	115.2	99.5	83.4	67.5
11.3	154.3	140.0	120.9	101.4	82.1	16.3	126.3	114.6	99.0	83.0	67.2
11.4	153.9	139.7	120.6	101.1	81.9	16.4	125.6	114.0	98.4	82.6	66.8
11.5	153.3	139.2	120.2	100.8	81.6	16.5	124.9	113.4	97.9	82.1	66.5
11.6	152.9	138.8	119.8	100.5	81.4	16.6	124.3	112.8	97.4	81.7	66.1
11.7	152.4	138.3	119.4	100.2	81.1	16.7	123.6	112.2	96.8	81.2	65.7
11.8	152.0	138.0	119.1	99.9	80.9	16.8	122.9	111.6	96.3	80.8	65.4
11.9	151.4	137.5	118.7	99.5	80.6	16.9	122.2	111.0	95.8	80.3	65.0
12.0	150.9	137.0	118.3	99.2	80.3	17.0	121.6	110.3	95.3	79.9	64.7
12.1	150.5	136.6	117.9	98.9	80.1	17.1	120.9	109.7	94.7	79.5	64.3
12.2	150.0	136.1	117.5	98.6	79.8	17.2	120.2	109.1	94.2	79.0	64.0
12.3	149.4	135.6	117.1	98.2	79.5	17.3	119.5	108.5	93.7	78.6	63.6
12.4	149.0	135.3	116.8	97.9	79.3	17.4	118.7	107.8	93.0	78.0	63.2
12.5	148.5	134.8	116.4	97.6	79.0	17.5	118.1	107.2	92.5	77.6	62.8
12.6	147.9	134.3	115.9	97.2	78.7	17.6	117.4	106.6	92.0	77.2	62.5
12.7	147.4	133.8	115.5	96.9	78.4	17.7	116.7	105.9	91.5	76.7	62.1
12.8	146.9	133.3	115.1	96.5	78.1	17.8	115.9	105.2	90.8	76.2	61.7
12.9	146.5	132.9	114.8	96.3	77.9	17.9	115.2	104.6	90.3	75.7	61.3
13.0	145.9	132.5	114.4	95.9	77.6	18.0	114.6	104.0	89.8	75.3	61.0
13.1	145.4	132.0	113.9	95.6	77.4	18.1	113.8	103.3	89.1	74.8	60.5
13.2	144.8	131.5	113.5	95.2	77.1	18.2	113.1	102.6	88.6	74.3	60.2
13.3	144.3	131.0	113.1	94.8	76.8	18.3	112.3	101.9	88.0	73.8	59.7
13.4	143.8	130.5	112.7	94.5	76.5	18.4	111.6	101.3	87.5	73.3	59.4
13.5	143.2	130.0	112.2	94.1	76.2	18.5	110.8	100.6	86.8	72.8	58.9
13.6	142.7	129.5	111.8	93.8	75.9	18.6	110.1	100.0	86.3	72.4	58.6
13.7	142.0	128.9	111.3	93.3	75.6	18.7	109.3	99.2	85.7	71.8	58.2
13.8	141.5	128.4	110.9	93.0	75.3	18.8	108.5	98.5	85.0	71.3	57.7
13.9	140.9	127.9	110.5	92.6	75.0	18.9	107.8	97.9	84.5	70.9	57.4
14.0	140.4	127.4	110.0	92.3	74.7	19.0	107.0	97.1	83.9	70.3	56.9
14.1	139.9	127.0	109.6	91.9	74.4	19.1	106.2	96.4	83.2	69.8	56.5
14.2	139.2	126.3	109.1	91.5	74.1	19.2	105.5	95.8	82.7	69.4	56.2
14.3	138.7	125.9	108.7	91.1	73.8	19.3	104.7	95.1	82.1	68.8	55.7
14.4	138.1	125.4	108.2	90.8	73.5	19.4	103.9	94.3	81.4	68.3	55.3
14.5	137.4	124.8	107.7	90.3	73.1	19.5	103.1	93.6	80.8	67.8	54.9
14.6	136.9	124.3	107.3	90.0	72.8	19.6	102.4	93.0	80.3	67.3	54.5
14.7	136.4	123.8	106.9	89.6	72.6	19.7	101.6	92.3	79.6	66.8	54.1
14.8	135.7	123.2	106.3	89.2	72.2	19.8	100.8	91.5	79.0	66.3	53.6
14.9	135.2	122.7	105.9	88.8	71.9	19.9	100.0	90.8	78.4	65.7	53.2
15.0	134.5	122.1	105.4	88.4	71.6	20.0	99.2	90.1	77.7	65.2	52.8

* From *Forest Products Laboratory's toughness-testing machine,* For. Prod. Lab. Rept. 1308, 1941.

Table 26. Calculated Toughness Values for Use with Forest Products Laboratory Toughness-Testing Machine*—*Continued*

Initial Angle 30° plus Friction

Final Angle, degrees	Position of Weight					Final Angle, degrees	Position of Weight				
	1	2	3	4	5		1	2	3	4	5
	wl = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716		*wl* = 1346	*wl* = 1222	*wl* = 1055	*wl* = 885	*wl* = 716
	In.-lb.						In.-lb.				
20.1	98.4	89.3	77.1	64.7	52.4	25.1	53.3	48.4	41.8	35.0	28.4
20.2	97.6	88.6	76.5	64.1	51.9	25.2	52.2	47.4	40.9	34.3	27.8
20.3	96.8	87.9	75.8	63.6	51.5	25.3	51.3	46.6	40.2	33.7	27.3
20.4	96.0	87.1	75.2	63.1	51.1	35.4	50.2	45.6	39.3	33.0	26.7
20.5	95.2	86.4	74.6	62.6	50.6	25.5	49.3	44.7	38.6	32.4	26.2
20.6	94.4	85.7	74.0	62.0	50.2	25.6	48.2	43.7	37.8	31.7	25.6
20.7	93.4	84.8	73.2	61.4	49.7	25.7	47.3	42.9	37.0	31.1	25.1
20.8	92.6	84.1	72.6	60.9	49.3	25.8	46.2	41.9	36.2	30.3	24.6
20.9	91.8	83.3	71.9	60.3	48.8	25.9	45.2	41.1	35.4	29.7	24.1
21.0	91.0	82.6	71.3	59.8	48.4	26.0	44.2	40.1	34.6	29.0	23.5
21.1	90.2	81.9	70.7	59.3	48.0	26.1	43.1	39.1	33.8	28.3	22.9
21.2	89.3	81.0	69.9	58.7	47.5	26.2	42.1	38.2	33.0	27.7	22.4
21.3	88.4	80.3	69.3	58.1	47.1	26.3	41.1	37.3	32.2	27.0	21.8
21.4	87.6	79.5	68.7	57.6	46.6	26.4	40.0	36.3	31.3	26.3	21.3
21.5	86.7	78.7	67.9	57.0	46.1	26.5	38.9	35.3	30.5	25.6	20.7
21.6	85.9	78.0	67.3	56.4	45.7	26.6	38.0	34.5	29.7	25.0	20.2
21.7	84.9	77.1	66.0	55.8	45.2	26.7	36.9	33.5	28.9	24.2	19.6
21.8	84.1	76.4	65.9	55.3	44.8	26.8	35.8	32.5	28.1	23.5	19.1
21.9	83.2	75.5	65.2	54.7	44.3	26.9	34.7	31.5	27.2	22.8	18.5
22.0	82.4	74.8	64.6	54.1	43.8	27.0	33.7	30.5	26.4	22.1	17.9
22.1	81.4	73.9	63.8	53.5	43.3	27.1	32.6	29.6	25.5	21.4	17.3
22.2	80.6	73.2	63.2	53.0	42.9	27.2	31.5	28.6	24.7	20.7	16.8
22.3	79.7	72.3	62.5	52.4	42.4	27.3	30.4	27.6	23.8	20.0	16.2
22.4	78.8	71.5	61.7	51.8	41.9	27.4	29.3	26.6	23.0	19.3	15.6
22.5	77.9	70.7	61.1	51.2	41.5	27.5	28.3	25.7	22.2	18.6	15.0
22.6	77.0	69.9	60.3	50.6	41.0	27.6	27.2	24.7	21.3	17.9	14.5
22.7	76.0	69.0	59.6	50.0	40.5	27.7	26.1	23.7	20.5	17.2	13.9
22.8	75.3	68.3	59.0	49.5	40.0	27.8	25.0	22.7	19.6	16.5	13.3
22.9	74.3	67.5	58.2	48.8	39.5	27.9	24.0	21.8	18.8	15.7	12.7
23.0	73.4	66.6	57.5	48.2	39.1	28.0	22.8	20.7	17.8	15.0	12.1
23.1	72.4	65.7	56.8	47.6	38.5	28.1	21.7	19.7	17.0	14.2	11.5
23.2	71.5	64.9	56.0	47.0	38.0	28.2	20.6	18.7	16.1	13.5	11.0
23.3	70.5	64.0	55.3	46.4	37.5	28.3	19.5	17.7	15.3	12.8	10.4
23.4	69.7	63.3	54.6	45.8	37.1	28.4	18.3	16.6	14.3	12.0	9.7
23.5	68.8	62.4	53.9	45.2	36.6	28.5	17.2	15.6	13.5	11.3	9.2
23.6	67.8	61.6	53.2	44.6	36.1	28.6	16.2	14.7	12.7	10.6	8.6
23.7	66.9	60.7	52.4	44.0	35.6	28.7	14.9	13.6	11.7	9.8	8.0
23.8	66.0	59.9	51.7	43.4	35.1	28.8	13.9	12.6	10.9	9.1	7.4
23.9	65.0	59.0	51.0	42.7	34.6	28.9	12.8	11.6	10.0	8.4	6.8
24.0	63.9	58.0	50.1	42.0	34.0	29.0	11.6	10.5	9.1	7.6	6.2
24.1	63.0	57.2	49.4	41.4	33.5	29.1	10.5	9.5	8.2	6.9	5.6
24.2	62.1	56.3	48.6	40.8	33.0	29.2	9.3	8.4	7.3	6.1	4.9
24.3	61.6	55.5	47.9	40.2	32.5	29.3	8.2	7.5	6.4	5.4	4.4
24.4	60.2	54.6	47.2	39.5	32.0	29.4	7.0	6.4	5.5	4.6	3.7
24.5	59.2	53.8	46.4	38.9	31.5	29.5	5.9	5.4	4.6	3.9	3.2
24.6	58.2	52.8	45.6	38.2	30.9	29.6	4.7	4.3	3.7	3.1	2.5
24.7	57.2	51.9	44.8	37.6	30.4	29.7	3.5	3.2	2.7	2.3	1.9
24.8	56.3	51.1	44.1	37.0	29.9	29.8	2.4	2.2	1.9	1.6	1.3
24.9	55.2	50.1	43.3	36.3	29.4	29.9	1.2	1.1	0.9	0.8	0.6
25.0	54.3	49.2	42.5	35.7	28.9	30.0	0.0	0.0	0.0	0.0	0.0

* From *Forest Products Laboratory's toughness-testing machine*, For. Prod. Lab. Rept. 1308 ,1941.

provide a convenient means of detecting brash material of low shock resistance. When used for this purpose, one or more specimens (preferably not less than four) should be taken from each piece of wood under consideration. To be acceptable for exacting use, the piece must (1) either meet a minimum toughness requirement established for the species in question, or if within a certain tolerance below the minimum, must pass, in addition, a prescribed specific-gravity limitation; (2) show a limited range in toughness values for all specimens from the same piece; and (3) pass careful visual inspection. The object of limiting the range in toughness values for specimens from any one piece of stock is to guard against pieces that contain minute compression failures or localized decay. Careful visual inspection is necessary to eliminate compression wood as well as cross grain and other defects.[26]

Other Tests

Many other kinds of tests are made as occasion demands. One group consists of those made on manufactured articles—packing boxes, crates, and other containers, vehicle and implement woods, crossarms, and the like—or materials used in the rough, such as poles and mine timbers. Such products are subjected to loading stresses approximating those that they would receive in service.

Another important type of test is that made on built-up structures, such as beams composed of small pieces bolted together, mortised joints, and timber trusses. Tests of this kind are worked out according to the specific requirements in each case.

Tests are also made to determine the nail-, screw-, and spike-holding powers of various woods and the efficiency of various forms of fastenings.

---

[26] The advantages of this method of testing for toughness are enumerated by Wilson (Impact tests of wood, footnote 15), as follows: The apparatus is relatively simple compared to that required for other tests, such as static bending; it can be easily operated by hand and, hence, can be placed where convenient without respect to sources of power; specimens are small and can be so taken as to represent very closely the beam, propeller lamination, or other part to be passed on; speed of test is automatically regulated and need not enter as a factor affecting results; results are less affected than those of other tests by differences of moisture content of the wood; and, as long as variations of moisture content do not exceed reasonable limits, no adjustment of results is necessary.

The methods of making most of these special tests are described in the indicated references in the following bibliography of standard and special tests.

REFERENCES

Tests on Small Clear Specimens

American Society for Testing Materials: Standard methods of testing small clear specimens of timber. Serial Designation: D143-48, 1948 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

———: Standard methods of testing plywood, veneer, and other wood and wood-base materials. Serial Designation: D805-47, 1947 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

Bethel, J. S., and Harrar, E. S.: A method of determining the specific gravity of small wood samples. *Tropical Woods,* New Haven, No. 93, Mar. 1, 1948, pp. 53–6.

Burgess, H. T., Kenneth Scott, and Bernice Albright: *Manual of methods and procedure in computing results of strength tests.* For. Prod. Lab., Madison, 1920.

Chaplin, C. J.: *Mechanical and physical properties of timbers—tests of small clear specimens.* For. Prod. Res. Lab. Proj. 1, London, 1928.

Chapman, R. W.: The strength of South Australian timbers. *Australian For. Jour.,* Sydney, Vol. 10, June 1927, pp. 143–7.

Forest Products Laboratory: *Wood handbook,* rev. U. S. Dept. Agr. Unnumbered Publ., Washington, 1940.

———: *Forest Products Laboratory's toughness-testing machine.* For. Prod. Lab. Rept. 1308, Madison, 1941.

———: *Design of wood aircraft structures.* ANC Bul. 18, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1944.

———: *Elastic properties of wood.* For. Prod. Lab. Rept. 1528 and Supplements A–H, Madison, 1945–46.

Forest Products Research Laboratory (England): *Handbook of empire timbers.* Dept. Sci. and Ind. Res., London, 1945.

Forest Research Institute (India): *Mechanical, physical, and structural properties of wood grown in India—tests on small clear specimens.* Scheme of Operation 1 for Proj. 1, Dehra Dun, India.

Hansen, Howard J.: *Modern timber design.* 2d ed. John Wiley & Sons, New York, 1948.

Julius, G. A.: *The physical characteristics of the hardwoods of Western Australia, with supplement.* 4th ed., rev. Perth, 1918.

Kynoch, William, and Newell A. Norton: *Mechanical properties of certain tropical woods, chiefly from South America.* Univ. Mich. School For. and Cons. Bul. 7, Ann Arbor, 1938.

MARCH, H. W.: *Stress–strain relations in wood and plywood considered as orthotropic materials.* For. Prod. Lab. Rept. 1503, Madison, 1944.

———, E. W. KUENZI, and W. J. KOMMERS: *Method of measuring the shearing moduli in wood.* For. Prod. Lab. Rept. 1301, Madison, 1941.

MARKWARDT, L. J.: *Comparative strength properties of woods grown in the United States.* U. S. Dept. Agr. Tech. Bul. 158, Washington, 1930.

———: *The distribution and the mechanical properties of Alaska woods.* U. S. Dept. Agr. Tech. Bul. 226, Washington, 1931.

——— and T. R. C. WILSON: *Strength and related properties of woods grown in the United States.* U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935.

NEW ZEALAND STATE FOREST SERVICE: *Mechanical properties of wood grown in New Zealand—tests on small clear specimens.* New Zealand State For. Serv. Section of Timber Mechanics, Proj. 1, Working Plan 1, Wellington, 1922.

NEWLIN, J. A., and T. R. C. WILSON: *Mechanical properties of woods grown in the United States.* U. S. Dept. Agr. Bul. 556, Washington, 1917.

NORRIS, C. B.: *The application of Mohr's stress and strain circles to wood and plywood.* For. Prod. Lab. Rept. 1317, Madison, 1943.

ROCHESTER, G. H.: *The mechanical properties of Canadian woods, together with their related physical properties.* Canada Dept. Int. For. Serv. Bul. 82, Ottawa, 1933.

STERNS, R W.: *Canadian Douglas fir—its mechanical and physical properties.* Canada Dept. Int. For. Serv. Bul. 60, Ottawa, 1918.

WARREN, W. H.: *The strength, elasticity, and other properties of New South Wales hardwood timbers.* N. S. W. Dept. For., Sydney, 1911.

WILSON, T. R. C.: Impact tests of wood. *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 22, Pt. 2, 1922, pp. 55–73.

———: *Strength–moisture relations for wood.* U. S. Dept. Agr. Tech. Bul. 282, Washington, 1932.

Tests on Structural Timbers

AMERICAN SOCIETY FOR TESTING MATERIALS: Standard specifications for structural wood joist and plank, beams and stringers, and posts and timbers. Serial Designation: D245-37, 1937 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

BETTS, H. S., and J. A. NEWLIN: *Strength tests of structural timbers treated by commercial wood-preserving processes.* U. S. Dept. Agr. Bul. 286, Washington, 1915.

CLINE, MCGARVEY, and A. L. HEIM: *Tests of structural timbers.* U. S. Dept. Agr. For. Serv. Bul. 108, Washington, 1912.

GREGORY, W. B.: Tests of creosoted timber. *Trans. Am. Soc. Civil Eng.,* New York, Vol. 76, 1913, pp. 1192–1203

HARKOM, J. F., and G. H. ROCHESTER.: *Strength tests of creosoted Douglas fir beams.* Canada Dept. Int. For. Serv. Circ. 28, Ottawa, 1930.

HATT, W. KENDRICK: *Experiments on the strength of treated timber.* U. S. Dept. Agr. For. Serv. Circ. 39, Washington, 1906.

Heck, G. E.: *Built-up southern yellow pine timbers tested for strength.* Series E-26, Nat. Lbr. Mfrs. Assn. Wood Const. Inf. Serv., Chicago, 1921.

McElhanney, T. A., and associates: *Canadian woods: their properties and uses.* Canada Dept. Int., Ottawa, 1935.

McFarland, H. B.: Tests of Douglas fir bridge stringers. *Proc. Am. Ry. Eng. Assn.,* Chicago, Vol. 17, Pt. 2, 1916, pp. 281–467.

———: Tests of long-leaf pine bridge timbers. *Ibid.,* Vol. 14, Pt. 2, 1913, pp. 31–184.

Markwardt, L. J.: Wood as an engineering material (Eighteenth Edgar Marburg lecture). *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 43, 1943, pp. 435–92.

National Lumber Manufacturers Association: *National design specification for stress-grade lumber and its fastenings,* rev. Washington, 1948.

Newlin, J. A., and J. M. Gahagan: *Tests of large timber columns and presentation of the Forest Products Laboratory column formula.* U. S. Dept. Agr. Tech. Bul. 167, Washington, 1930.

——— and R. P. A. Johnson: *Basic grading rules and working stresses for structural timbers.* U. S. Dept. Agr. Dept. Circ. 295, Washington, 1923.

——— and ———: Structural timbers—defects and their influence on strength. *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 24, Pt. 2. 1924, pp. 975–87.

Schrader, O. Harry, Jr.: Tests on creosoted laminated stringers. *Eng. News-Record,* New York, Vol. 135, No. 20, Nov. 15, 1945, pp. 80–3.

Seaman, L. N.: *Tests of Indian timbers in structural sizes.* Scheme of Operation 1 for Proj. 2, For. Res. Inst., Dehra Dun, India, 1925.

Talbot, Arthur N.: *Tests of timber beams.* Univ. Ill. Eng. Expt. Sta. Bul. 41, Urbana, 1909.

Underwriters Laboratories: *Fire tests of building columns.* Chicago, 1921.

Wilson, T. R. C.: *Guide to the grading of structural timbers and the determination of working stresses.* U. S. Dept. Agr. Misc. Publ. 185, Washington, 1934. Also Supplement 1, For. Prod. Lab. Rept. R1225 (1940) and Supplement 2, For. Prod. Lab. Rept. R1715 (1948).

——— and W. S. Cottingham: *Tests of glued laminated wood beams and columns and development of principles of design.* For. Prod. Lab. Rept. R1687, Madison, 1947.

Tests on Poles and Piling

American Standards Association: *American standard specifications and dimensions for wood poles.* Standard 05.1-1948, New York, 1948.

———: *American standard specifications for round timber piles.* Standard 06-1939, New York, 1939.

Betts, Norman de W., and A. L. Heim: *Tests of Rocky Mountain woods for telephone poles.* U. S. Dept. Agr. Bul. 67, Washington, 1914.

Browne, William Hand, Jr., and James Fontaine: *Tests of North Carolina poles for electric distribution lines.* N. C. State Coll. Eng. Expt. Sta. Bul. 3. Raleigh, 1929.

McElhanney, T. A., and associates: *Canadian woods: their properties and uses.* Canada Dept. Int., Ottawa, 1935.

——— and R. S. Perry: Report on tests of the relative strength of green-cut and fire-killed western cedar pole timber. *Western Lumberman,* Vancouver, B. C., Vol. 25, Sept. 1928, pp. 886, 896–7.

McFarland, H. B.: Tests of Oregon fir piling. *Bul. Am. Ry. Eng. Assn.,* Chicago, Vol. 16, Aug. 1914.

Perry, R. S., and T. A. McElhanney: *Tests of green-cut western cedar poles.* Canada Dept. Int. For. Serv. Circ. 21, Ottawa, 1927.

Rochester, G. H.: *The strength of telephone poles.* Canada Dept. Int. For. Serv. Circ. 31, Ottawa, 1931.

Wilson, T. R. C.: *Results of some strength tests on wooden poles.* For. Prod. Lab. Rept. 763, Madison, 1923.

———: *Fiber stresses for wood poles.* For. Prod. Lab. Rept. 1619, Madison, 1946.

Winchester, Laurence S.: An experimental determination of the strength of full-sized telephone poles. *Electrical World,* New York, Vol. 57, Mar. 16, 1911, pp. 667–71.

Tests on Crossarms

Dibble, A. M.: *Strength of cross-arms.* New Zealand State For. Serv. Circ. 10, Wellington, 1926.

Eggleston, Richard C.: *Strength tests of wood cross-arms.* Bell Telephone System Mono. B-1563, New York, 1948.

Grondal, B. L.: *Strength tests on solid and laminated cross-arms.* Univ. Wash. Eng. Expt. Sta. Bul. 47, Seattle, 1928.

Wilson, Thomas R. C.: *Strength tests of cross-arms.* U. S. Dept. Agr. For. Serv. Circ. 204, Washington, 1912.

Tests on Mine Timbers

Betts, Norman de W.: *Rocky Mountain mine timbers.* U. S. Dept. Agr. Bul. 77, Washington, 1914.

Johnson, R. P. A.: *The strength of mine timbers.* Am. Mining Cong. Standardiz. Bul. 4, 1924.

Rice, George S.: *Tests of strength of roof supports used in anthracite mines of Pennsylvania.* U. S. Dept. Comm. Bur. Mines Bul. 303, Washington, 1929.

Tests on Aircraft Parts

Boyd, James E.: *Investigations of the compressive strength of spruce struts of rectangular cross section and the derivation of formulas suitable for use in airplane design.* U. S. Dept. Comm. Nat. Bur. Standards Tech. Paper 152, Washington, 1920.

ELMENDORF, A.: Testing strength of airplane wing ribs 55 to 96 inches. *Automotive Ind.*, Chicago., Vol. 41, July 31, 1919, pp. 209–13.

FOREST PRODUCTS LABORATORY: *Wood in aircraft construction,* U. S. Navy Dept., Aircraft Design Data Note 12, Washington, 1919, pp. 96–139.

———: *Wood aircraft inspection and fabrication.* ANC Bul. 19, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1943.

———: *Design of wood aircraft structures.* ANC Bul. 18, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1944.

———: *Methods for testing and evaluating cargo flooring for transport aircraft.* For. Prod. Lab. Rept. 1550 and Supplements A–E, Madison, 1947–48.

HECK, G. E.: Splintering properties of airplane woods (under rifle fire). *Automotive Ind.*, Chicago, Vol. 40, June 5, 1919, pp. 1234–5.

HEIM, A. L., A. C. KNAUSS, and LOUIS SEUTTER: *Internal stresses in laminated construction.* Nat. Advis. Comm. Aero. Rept. 145, Washington, 1922.

MARKWARDT, L. J.: *Aircraft woods—their properties, selection, and characteristics.* Nat. Advis. Comm. Aero. Rept. 354, Washington, 1930.

NELSON, JOHN H.: *The strength of one-piece solid, built-up, and laminated wood airplane wing beams.* Nat. Adv. Comm. Aero. Rept. 35, Washington, 1919.

NEWLIN, J. A., and G. W. TRAYER: *The influence of the form of a wooden beam on its stiffness and strength: I. Deflection of beams with special reference to shear deformation; II. Form factors of beams subjected to transverse loading only;* and *III. Stresses in wood members subjected to combined column and beam action.* Nat. Advis. Comm. Aero. Repts. 180, 181, and 188, Washington, 1924.

———: *The design of airplane wing ribs.* Nat. Adv. Comm. Aero. Rept. 345, Washington, 1930.

———: *A method of calculating the ultimate strength of continuous beams.* Nat. Adv. Comm. Aero. Rept. 347, Washington, 1930.

TRAYER, GEORGE W., and H. W. MARCH: *The torsion of members having sections common in aircraft construction.* Nat. Adv. Comm. Aero. Rept. 334, Washington, 1930.

——— and ———: *Elastic instability of members having sections common in aircraft construction.* Nat. Adv. Comm. Aero. Rept. 382, Washington, 1931.

Tests on Shipping Containers

CARLSON, T. A.: *Corrugated board and its component parts as engineering materials.* Am. Management Assn. Prod. Ser. 128, 1941.

———: *Research in the use of wood for containers.* Nat. Farm Chemurgic Counc. Paper 507, Columbus, 1946.

———: *Side lights on the revolving drum test for boxes.* Am. Management Assn. Packaging Ser. 18, New York, 1946.

FOREST PRODUCTS LABORATORY: *Tests for shipping containers in revolving* *hexagonal drum box-testing machines.* For. Prod. Lab. Rept. R1462, Madison, 1944.

Heck, G. E.: *Design factors affecting the strength and rigidity of wooden crates.* U. S. Dept. Agr. Circ. 236, Washington, 1932.

National Association Box Manufacturers: *Wooden box and crate construction.* Chicago, 1921.

Newlin, John A.: *Tests of packing boxes of various forms.* U. S. Dept. Agr. For. Serv. Circ. 214, Washington, 1913.

———: *Tests of wooden barrels.* U. S. Dept. Agr. Bul. 86, Washington, 1914.

——— and T. R. C. Wilson: The development of a box testing machine and some results of tests. *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 16, Pt. 2, 1916, pp. 320–42.

Plaskett, C. A.: *Principles of box and crate construction.* U. S. Dept. Agr. Tech. Bul. 171, Washington, 1930.

Ward, W. C.: *Butter-box tests.* New Zealand State For. Serv. Circ. 23, Wellington, 1926.

Tests on Plywood

American Society for Testing Materials: Standard methods for testing plywood, veneer, and other wood and wood-base materials. Serial Designation: D805-47, 1947 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

Elmendorf, Armin: *Data on the design of plywood for aircraft.* Rept. No. 84, U. S. Nat. Advis. Comm. Aero., Washington, 1920.

Forest Products Laboratory: *Wood in aircraft construction.* U. S. Navy Dept. Bur. Const. and Rep., Aircraft Design Data Note 12, Washington, 1919, pp. 59–90.

———: *Data on the design of plywood for aircraft.* For. Prod. Lab. Rept. 1302, Madison, 1941.

———: *Buckling of flat plywood plates in compression, shear, or combined compression and shear.* For. Prod. Lab. Rept. 1316 and Supplements A–I, Madison, 1942–45.

———: *Wood aircraft inspection and fabrication.* ANC Bul. 19, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1943.

———: *Buckling of long, thin, plywood cylinders in axial compression.* For. Prod. Lab. Rept. 1322 and Supplements A–B, Madison, 1943.

———: *Design of plywood webs in box beams.* For. Prod. Lab. Rept. 1318 and Supplements A–E, Madison, 1943–44.

———: *Design of wood aircraft structures.* ANC Bul. 18, Army–Navy–Civil Comm. on Aircraft Design Criteria, Aero. Board, Washington, 1944.

———: *Methods of conducting buckling tests of plywood panels in compression.* For. Prod. Lab. Rept. 1554, Madison, 1946.

Freas, Alan D.: *Methods of computing the strength and stiffness of plywood strips in bending.* For. Prod. Lab. Rept. 1304, Madison, 1942.

Kommers, W. J.: *The fatigue behavior of wood and plywood subjected to* *repeated and reversed bending stresses.* For Prod. Lab. Rept. 1327 and Supplement A, Madison, 1943–44.

Liska, J. A.: *Methods of calculating the strength and modulus of elasticity of plywood in compression.* For. Prod. Lab. Rept. 1315, rev., Madison, 1946.

March, H. W.: *Flat plates of plywood under uniform or concentrated loads.* For. Prod. Lab. Rept. 1312, Madison, 1942.

———: *Stress–strain relations in wood and plywood considered as orthotropic materials.* For. Prod. Lab. Rept. 1503, Madison, 1944.

Markwardt, L. J., and A. D. Freas: *Approximate methods of calculating the strength of plywood.* For. Prod. Lab. Rept. R1630, rev., Madison, 1946.

——— and A. Elmendorf: Mechanical tests made on plywood. *Hardwood Record,* Chicago, Vol. 47, July 10, 1919, pp. 23, 26, 28.

Norris, C. B.: *The application of Mohr's stress and strain circles to wood and plywood.* For. Prod. Lab. Rept. 1317, Madison, 1943.

——— and P. F. McKinnon: *Compression, tension, and shear tests on yellow-poplar plywood panels of sizes that do not buckle with tests made at various angles to the face grain.* For. Prod. Lab. Rept. 1328 and Supplements A–C, Madison, 1943–46.

———, Fred Werren, and P. F. McKinnon: *The effect of veneer thickness and grain direction on the shear strength of plywood.* For. Prod. Lab. Rept. 1801, Madison, 1948.

Perry, Thomas D.: *Modern plywood.* 2d ed., Pitman Publ. Corp., New York, 1948.

Trayer, G. W.: *Design of plywood webs for airplane wing beams.* Nat. Adv. Comm. Aero. Rept. 344, Washington, 1930.

Tests on Fastenings

Anonymous: Tests of holding power of nails in Douglas fir and western hemlock. *Timberman,* Portland, Oreg., Vol. 18, Oct. 1917, pp. 37–41.

Beyer, Albin H., and William J. Krefeld: *Tests on the holding power of railroad spikes.* Columbia Univ. Dept. Civil Eng. Bul. 1, New York, 1919.

Cockrell, Robert A.: *A study of the screw-holding properties of wood.* N. Y. State Coll. For. Tech. Publ. 44, Syracuse, 1933.

Dewall, H. D.: Tests of some joints used in heavy timber framing. *Eng. News,* New York, Vol. 71, Mar. 19, 1914, pp. 593–8, and Mar. 26, 1914, pp. 666–9.

Fairchild, I. J.: *Holding power of wood screws.* U. S. Dept. Comm. Nat. Bur. Standards Tech. Paper 319, Washington, 1926.

Forest Products Laboratory: *Bolt-bearing strength of wood and modified wood.* For. Prod. Lab. Rept. 1523 and Supplements A–D, Madison, 1944–46.

———: *Wood handbook,* rev. U. S. Dept. Agr. Unnumbered Publ., Washington, 1940.

Hatt, W. Kendrick: *Holding force of railroad spikes in wooden ties.* U. S. Dept. Agr. For. Serv. Circ. 46, Washington, 1906.

Heck, G. E.: Description of the pendulum machine for driving and pulling nails. *Barrel and Box,* Chicago, Vol. 30, Nov. 1925, pp. 45–7.

Markwardt, L. J., and J. M. Gahagan: Nail-holding power of various species of wood. *Am. Lumberman,* Chicago, No. 2826, July 13, 1929, pp. 58–9; also in *Southern Lumberman,* Nashville, Tenn., Vol. 136, July 15, 1929, pp. 55–6; and in *Timberman,* Portland, Oreg., Vol. 30, Aug. 1929, pp. 142–3.

McFarland, H. B.: (1) Comparative holding power of different pointed Goldie and cut spikes; (2) Holding power of cut and screw spikes. *Proc. Am. Ry. Eng. Assn.,* Chicago, Vol. 15, 1914, pp. 766–97.

National Lumber Manufacturers Association: *National design specification for stress-grade lumber and its fastenings,* rev., Washington, 1948.

Newlin, J. A., and J. M. Gahagan: *Lag-screw joints: their behavior and design.* U. S. Dept. Agr. Tech. Bul. 597, Washington, 1938.

Perkins, N. S., Peter Landsen, and G. W. Trayer: *Modern connectors for timber construction.* U.S. Dept. Comm. Nat. Com. on Wood Utiliz., Washington, 1933.

Scholton, J. A.: *Timber-connector joints: their strength and design.* U. S. Dept. Agr. Tech. Bul. 865, Washington, 1944.

Trayer, G. W.: *The bearing strength of wood under bolts.* U. S. Dept. Agr. Tech. Bul. 332, Washington, 1932.

Wilson, T. R. C.: Tests made to determine lateral resistance of wire nails. *Eng. Record,* New York, Vol. 75, Feb. 24, 1917, pp. 303–04.

Zimmerman, C. W.: Tests of the holding force of common and screw spikes in natural and treated Douglas fir ties. *West Coast Lumberman,* Seattle, Vol. 43, Nov. 15, 1922, pp. 32, 34, 39.

Miscellaneous Tests

Cartwright, F. P.: Tests made by U. S. Forest Products Laboratory reveal new facts about frame construction. *Am. Arch.,* New York, Vol. 137, Feb. 1930, pp. 30–3.

Erickson, E. C. O.: *Strength tests of spliced studs.* For. Prod. Lab. Rept. 1275, Madison, 1941.

———: *Mechanical properties of laminated modified wood.* For. Prod. Lab. Rept. 1639, Madison, 1947.

Forest Products Laboratory: *Methods of test for evaluating the properties of building boards.* For. Prod. Lab. Rept. R1712, Madison, 1948.

Geisler, Carl H.: An accelerated abrasion test. *Jour. Am. Ceramic Soc.,* Columbus, Ohio, Vol. 9, Mar. 1926.

Holroyd, H. B., and H. S. Betts: *Tests of vehicle and implement woods* U. S. Dept. Agr. For. Serv. Circ. 142, Washington, 1908.

Kessler, D. W.: The development of an apparatus for wear tests on flooring materials. *Proc. Am. Soc. Test. Mat.,* Philadelphia, Vol. 28, Pt. 2, 1928, pp. 855–67.

Lewis, W. C.: *Effect of size and shape of specimen on the tensile strength of fiberboards.* For. Prod. Lab. Rept. R1716, Madison, 1948.

Luxford, R. F., and R. H. Krone: *Laminated oak frames for a 50-foot*

Navy motor launch compared to steam bent frames. For. Prod. Lab. Rept. 1611, Madison, 1946.

McDaniel, A. B.: Eight-inch hardwood rollers take 12 to 18 tons per foot. *Eng. News-Record,* New York, Vol. 80, Jan. 17, 1918, pp. 123–4.

Platow, R. C., and A. G. H. Dietz: *Strength properties* (of adhesives). Symposium on adhesives, Am. Soc. Test. Mat., Philadelphia, 1945, pp. 25–35.

Trayer, George W.: Tests of frame wall construction. *Eng. News-Record,* New York, Vol. 103, Oct. 24, 1929, pp. 656–7.

———: *The rigidity and strength of frame walls.* For. Prod. Lab. Rept. 896, rev., Madison, 1947.

Truax, T. R.: *The gluing of wood.* U. S. Dept. Agr. Dept. Bul. 1500, Washington, 1929

———, F. L. Browne, and Don Brouse: The significance of mechanical wood joint tests for the selection of woodworking glues. *Ind. and Eng. Chem.,* Washington, Vol. 21, Jan. 1929, pp. 74–9.

Wangaard, F. F.: *Summary of information on the durability of woodworking glues.* For. Prod. Lab. Rept. 1530, Madison, 1946.

Wilson, G. S.: *An investigation of compressed spruce pulleys.* Univ. Wash. Eng. Expt. Sta., Bul. 10, Seattle, 1920.

Wilson, T. R. C.: Some tests of end-matched lumber. *Southern Lumberman,* Nashville, Tenn., Vol. 133, Dec. 22, 1928, pp. 197–202.

Youngquist, W. G., and Bert P. Munthe: *The effect of a change in testing speed and span on the flexural strength of insulating and structural fiberboards and a proposed new method of test.* For. Prod. Lab. Rept. R1717, Madison, 1948.

APPENDIX

Table 27. Nomenclature of American Woods*

Hardwoods

Common Name	Scientific Name
Alder, red	*Alnus rubra*
Apple	*Malus pumila*
Ash, Biltmore	*Fraxinus biltmoreana*
Ash, black	*Fraxinus nigra*
Ash, blue	*Fraxinus quadrangulata*
Ash, green	*Fraxinus pennsylvanica lanceolata*
Ash, Oregon	*Fraxinus oregona*
Ash, pumpkin	*Fraxinus tomentosa*
Ash, white	*Fraxinus americana*
Aspen	*Populus tremuloides*
Aspen, largetooth	*Populus grandidentata*
Basswood	*Tilia americana*
Beech	*Fagus grandifolia*
Beech, blue (Hornbeam, American)	*Carpinus caroliniana*
Birch, Alaska white	*Betula papyrifera neoalaskana*
Birch, gray	*Betula populifolia*
Birch, paper	*Betula papyrifera*
Birch, sweet	*Betula lenta*
Birch, yellow	*Betula lutea*
Blackwood	*Avicennia nitida*
Buckeye, yellow	*Aesculus octandra*
Bustic	*Dipholis salicifolia*
Butternut	*Juglans cinerea*
Buttonwood	*Conocarpus erecta*
Cascara	*Rhamnus purshiana*
Catalpa, hardy	*Catalpa speciosa*
Cherry, black	*Prunus serotina*
Cherry, pin	*Prunus pennsylvanica*
Chestnut	*Castanea dentata*
Chinquapin, golden	*Castanopsis chrysophylla*
Cottonwood, eastern	*Populus deltoides*
Cottonwood, northern black	*Populus trichocarpa hastata*
Dogwood	*Cornus florida*
Dogwood, Pacific	*Cornus nuttalli*
Elder, blueberry	*Sambucus glauca*

---

* The names contained in this list are those referred to in the text. Technical names from *Check list of the native and naturalized trees of the United States including Alaska.* Committee on Tree and Range Plant Names, U. S. Dept. Agr. For. Serv., Washington, 1944.

TABLE 27. NOMENCLATURE OF AMERICAN WOODS—*Continued*

Hardwoods—*continued*

Common Name	Scientific Name
Elm, American (Elm, white)	*Ulmus americana*
Elm, rock	*Ulmus thomasi*
Elm, slippery	*Ulmus fulva*
Fig, golden	*Ficus aurea*
Gum, black (Tupelo, black)	*Nyssa sylvatica*
Gum, blue	*Eucalyptus globulus*
Gum, red (Gum, sweet)	*Liquidambar styraciflua*
Gum, tupelo (Tupelo, water)	*Nyssa aquatica*
Gumbo limbo	*Bursera simaruba*
Hackberry	*Celtis occidentalis*
Haw, pear	*Crataegus tomentosa*
Hickory, bigleaf shagbark	*Carya laciniosa*
Hickory, bitternut	*Carya cordiformis*
Hickory, mockernut	*Carya tomentosa*
Hickory, nutmeg	*Carya myristicaeformis*
Hickory, pignut	*Carya glabra*
Hickory, shagbark	*Carya ovata*
Hickory, water	*Carya aquatica*
Holly	*Ilex opaca*
Honeylocust	*Gleditsia triacanthos*
Hophornbeam	*Ostrya virginiana*
Inkwood	*Exothea paniculata*
Ironwood, black (Leadwood)	*Krugiodendron ferreum*
Laurel, California	*Umbellularia californica*
Laurel, mountain	*Kalmia latifolia*
Locust, black	*Robinia pseudoacacia*
Madrono, Pacific	*Arbutus menziesii*
Magnolia, cucumber	*Magnolia acuminata*
Magnolia, evergreen	*Magnolia grandiflora*
Magnolia, mountain	*Magnolia fraseri*
Mangrove	*Rhizophora mangle*
Maple, bigleaf	*Acer macrophyllum*
Maple, black	*Acer nigrum*
Maple, red	*Acer rubrum*
Maple, silver	*Acer saccharinum*
Maple, striped	*Acer pennsylvanicum*
Maple, sugar	*Acer saccharum or A. saccharophorum*
Mastic	*Sideroxylon foetidissimum*
Oak, black	*Quercus velutina*
Oak, bur	*Quercus macrocarpa*
Oak, California black	*Quercus kelloggii*
Oak, canyon live	*Quercus chrysolepis*
Oak, chestnut	*Quercus montana*
Oak, laurel	*Quercus laurifolia*
Oak, live	*Quercus virginiana*

Table 27. Nomenclature of American Woods—*Continued*

Hardwoods—*continued*

Common Name	Scientific Name
Oak, Oregon white	*Quercus garryana*
Oak, pin	*Quercus palustris*
Oak, post	*Quercus stellata*
Oak, northern red	*Quercus borealis*
Oak, Rocky Mountain white (Oak, Gambel)	*Quercus gambelii*
Oak, scarlet	*Quercus coccinea*
Oak, southern red	*Quercus falcata*
Oak, swamp red	*Quercus falcata pagodaefolia*
Oak, swamp chestnut	*Quercus prinus*
Oak, swamp white	*Quercus bicolor*
Oak, water	*Quercus nigra*
Oak, white	*Quercus alba*
Oak, willow	*Quercus phellos*
Osage-orange	*Maclura pomifera*
Palmetto, cabbage	*Sabal palmetto*
Paradise tree	*Simarouba glauca*
Pecan	*Carya illinoensis*
Persimmon	*Diospyros virginiana*
Pigeon-plum	*Coccolobis laurifolia*
Poisonwood	*Metopium toxiferum*
Poplar, balsam	*Populus tacamahacca*
Poplar, yellow	*Liriodendron tulipifera*
Rhododendron, great	*Rhododendron maximum*
Sassafras	*Sassafras albidum*
Serviceberry	*Amelanchier arborea*
Silverbell	*Halesia carolina*
Sourwood	*Oxydendrum arboreum*
Stopper, red	*Eugenia confusa*
Sugarberry	*Celtis laevigata*
Sumach, staghorn	*Rhus typhina*
Sycamore	*Platanus occidentalis*
Walnut, black	*Juglans nigra*
Walnut, little	*Juglans rupestris*
Willow, black	*Salix nigra*
Willow, western black	*Salix lasiandra*
Witch-hazel	*Hamamelis virginiana*

Softwoods

Common Name	Scientific Name
Cedar, Alaska	*Chamaecyparis nootkatensis*
Cedar, incense	*Libocedrus decurrens*
Cedar, Port Orford	*Chamaecyparis lawsoniana*
Cedar, eastern red	*Juniperus virginiana*
Cedar, southern red	*Juniperus* sp.

Table 27. Nomenclature of American Woods—*Continued*

Softwoods—*continued*

Common Name	Scientific Name
Cedar, western red	*Thuja plicata*
Cedar, northern white	*Thuja occidentalis*
Cedar, southern white (Cedar, Atlantic white)	*Chamaecyparis thyoides*
Cypress, southern (Cypress, bald)	*Taxodium distichum*
Douglas fir (coast type)	*Pseudotsuga taxifolia*
Douglas fir (intermediate type)	*Pseudotsuga taxifolia*
Douglas fir (Rocky Mountain type)	*Pseudotsuga taxifolia*
Fir, alpine	*Abies lasiocarpa*
Fir, balsam	*Abies balsamea*
Fir, corkbark	*Abies lasiocarpa arizonica*
Fir, lowland white	*Abies grandis*
Fir, noble	*Abies nobilis or A. procera*
Fir, California red	*Abies magnifica*
Fir, silver	*Abies amabilis*
Fir, white	*Abies concolor*
Hemlock, eastern	*Tsuga canadensis*
Hemlock, mountain	*Tsuga mertensiana*
Hemlock, western	*Tsuga heterophylla*
Juniper, alligator	*Juniperus pachyphloea*
Larch, western	*Larix occidentalis*
Pine, jack	*Pinus banksiana*
Pine, Jeffrey	*Pinus jeffreyi*
Pine, limber	*Pinus flexilis*
Pine, loblolly	*Pinus taeda*
Pine, lodgepole	*Pinus contorta latifolia*
Pine, longleaf	*Pinus palustris*
Pine, mountain	*Pinus pungens*
Pine, northern white (eastern white)	*Pinus strobus*
Pine, Norway (red)	*Pinus resinosa*
Pine, pitch	*Pinus rigida*
Pine, pond	*Pinus rigida serotina*
Pine, ponderosa	*Pinus ponderosa*
Pine, sand	*Pinus clausa*
Pine, shortleaf	*Pinus echinata*
Pine, slash	*Pinus caribaea*
Pine, sugar	*Pinus lambertiana*
Pine, western white	*Pinus monticola*
Pinyon	*Pinus edulis*
Redwood (virgin)	*Sequoia sempervirens*
Redwood (second growth, openly grown)	*Sequoia sempervirens*
Redwood (second growth, closely grown)	*Sequoia sempervirens*
Spruce, black	*Picea mariana*
Spruce, Engelmann	*Picea engelmanni*
Spruce, red	*Picea rubens*

TABLE 27. NOMENCLATURE OF AMERICAN WOODS—*Continued*

Softwoods—*continued*

Common Name	Scientific Name
Spruce, Sitka	*Picea sitchensis*
Spruce, white	*Picea glauca*
Tamarack	*Larix laricina*
Yew, Pacific	*Taxus brevifolia*

Sample Working Plan[1]

MECHANICAL AND PHYSICAL PROPERTIES OF WOODS TESTS ON SMALL CLEAR SPECIMENS

Introduction

PURPOSE OF TESTS

The tests on small clear specimens of wood here outlined are made to afford:

1. Data for comparing the mechanical properties of various species.

2. Data for the establishment of correct strength functions which, in conjunction with results of tests of timbers in structural sizes, serve as a basis for fixing allowable stresses.

---

[1] The information contained herein is taken largely from Standard methods of testing small clear specimens of timber, Serial Designation: D143-48, 1948 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

See also L. J. Markwardt and T. R. C. Wilson, *Strength and related properties of woods grown in the United States,* U. S. Dept. Agr. Tech. Bul. 479, Washington, 1935.

For working plan for tests on structural timbers see Standard methods of conducting static tests of timbers in structural sizes, Serial Designation: D198-27, 1927 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II, which has also been approved as American Standard by the American Standards Association.

For working plan for tests on plywood and wood-base materials see Standard methods of testing plywood, veneer, and other wood and wood-base materials, Serial Designation: D805-47, 1947 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

3. Data on which to determine the influence on the mechanical properties of such factors as density, locality of growth, position in cross section, height of timber in the tree, change of properties with seasoning, and change from sapwood to heartwood.

KIND OF TESTS

The principal tests used to determine mechanical properties are as follows:

(*a*) Static bending.
(*b*) Compression parallel to grain.
(*c*) Compression perpendicular to grain.
(*d*) Shear parallel to grain.
(*e*) Tension parallel to grain.
(*f*) Tension perpendicular to grain.
(*g*) Impact bending.
(*h*) Toughness.
(*i*) Cleavage.
(*j*) Hardness.

In addition, such physical properties as specific gravity, and radial, tangential, and volumetric shrinkage are determined.

Material

COLLECTION

Selection. The material shall be from trees selected in the forest by one qualified to identify the species. For each species to be tested from a given locality, at least five representative trees of merchantable size and of approximately average age shall be selected if the trees are over 24 inches d.b.h. A minimum of ten representative trees will be required if the trees are 24 inches or less in d.b.h.

The material from the trees of each species from a given locality shall be selected as follows:

From one of these trees (two if 24 inches or less in d.b.h.), the following 8-foot sections, each representing two 4-foot bolts:[2]

---

[2] This tree is intended to furnish test material for studying, among other things, the variation of properties with height in trees and provides for this purpose an 8-foot section from different heights. Bolts are designated as *a*, *b*, *c*, etc., to represent successive 4-foot lengths taken above the stump. Bolt *a* is the 4-foot section taken immediately above the stump.

Length of Merchantable Bole, ft.	Bolts to Be Selected
16	*a*, *b*; *c*, *d*
20	*a*, *b*; *c*, *d*
24	*a*, *b*; *c*, *d*; *e*, *f*
28	*a*, *b*; *c*, *d*; *f*, *g*
32	*a*, *b*; *c*, *d*; *g*, *h*
36	*a*, *b*; *c*, *d*; *h*, *i*
40	*a*, *b*; *c*, *d*; *g*, *h*; *i*, *j*
44	*a*, *b*; *c*, *d*; *g*, *h*; *j*, *k*
48	*a*, *b*; *c*, *d*; *g*, *h*; *k*, *l*
52	*a*, *b*; *c*, *d*; *g*, *h*; *l*, *m*
56	*a*, *b*; *c*, *d*; *g*, *h*; *m*, *n*
60	*a*, *b*; *c*, *d*; *i*, *j*; *n*, *o*
64	*a*, *b*; *c*, *d*; *i*, *j*; *o*, *p*
72	*a*, *b*; *c*, *d*; *i*, *j*; *q*, *r*
80	*a*, *b*; *c*, *d*; *i*, *j*; *o*, *p*; *s*, *t*
96	*a*, *b*; *c*, *d*; *i*, *j*; *o*, *p*; *w*, *x*
Over 96	*a*, *b*; *c*,*d*; *k*,*l*; *s*, *t*; and last two 4-ft. bolts at top of merchantable length

From the remaining trees, the 8-foot section (bolts *c* and *d*) next above the 8-foot butt log.

In cases where the logs or bolts are over 60 inches in diameter, a single flitch 6 inches in thickness, taken through the pith in a north and south direction and representing the full diameter of the log, may be substituted, in the same length, for the full log or bolt specified in the preceding paragraphs.

Field Marking. Each tree shall be given an arabic number, the numbering in any given shipment to be consecutive for trees of a given species. Each 4 feet of length of a tree or log shall be considered a "bolt." Bolts shall be designated by small letters, beginning with *a* for the 4-foot section next above the stump. Bolt letters, therefore, indicate position with respect to height in tree.

The tree number and bolt designation shall be plainly marked on each log selected by the collector. Thus the 16-foot butt log of Tree 2 would be designated 2*abcd*. Steel dies are recommended for marking the butt end of the logs.

The north side of each log shall be indicated in some convenient manner.

All material collected from a given locality and shipped at one time shall be given a shipment number or other designation.

Field Descriptions. Complete field notes describing the material shall be fully and carefully made by the collector. These notes shall, in general, supply data as outlined in Table 28.

Photographs of the standing trees selected shall be taken.

TABLE 28. SHIPMENT DESCRIPTION—FIELD NOTES

Date..

Shipment No......................Species..Project No......................

State...County..

Local contact: National Forest...............................Private owner...............................

Name...Address...

....

A. General ecological description of locality:*

1. Climatic factors:
    - (*a*) Precipitation in inches: average annual amount.....................; seasonal distribution: spring................., summer...................., autumn...................., winter...................
    - (*b*) Temperature, degrees Fahrenheit: mean annual............................., mean summer................., mean winter................., maximum summer................., minimum winter.................

      Season between killing frosts: (dates).........................to.........................
    - (*c*) Relative humidity: high, medium, or low in spring..................................; summer.........................; autumn.........................; winter.........................
    - (*d*) Prevailing wind direction: summer.........................winter.........................
2. Topographic factors:
    - (*a*) Character of topography: level, rolling, mountainous, to precipitous ....
    - (*b*) Elevation: absolute..............................., relative..............................
    - (*c*) Presence of streams, lakes, swamps: numerous, few, permanent, intermittent..
    - (*d*) Geological history: original rock formations: (1) igneous, (2) sedimentary: shales, sandstones, limestones..
      ....
      Secondary formations: local, glacial, alluvial, loessal...................................
      ....
      ....

---

* Prepare page 1 of this form for each shipment. Underline descriptive words and fill in all blank spaces that apply. Use reverse of this form for additional notes.

From *Standard methods of testing small clear specimens of timber.* Serial designation D143-48, Am. Soc. Test. Mat., Philadelphia, 1948.

TABLE 28. SHIPMENT DESCRIPTION—FIELD NOTES—*Continued*

Date..

Shipment No.......................Species...Project No......................

State.....................Co....................Twp....................Range....................Sec....................

Locate on map or sketch;...................miles to..

B. Site description:†

1. Site quality class: I, II, III, IV, V; or age......................, height......................of dominant trees
2. Physiography
   - (*a*) Elevation: absolute.............................., range over area..............................
   - (*b*) Surface: level, undulating; slope.............., upper.............., lower.............., degree..............; ridge, valley bottom
   - (*c*) Aspect: N, NE, E, SE, S, SW, W, NW
   - (*d*) Distance to streams, lakes, swamps...
   - (*e*) Soil type: sand, sandy loam, loam, clay loam, clay
     U.S. Soil Survey name..
     - (1) Color............................(2) acid or alkaline, (3) depth............................
     - (4) boulders, stones, or gravel............................
   - (*f*) Soil moisture: dry, moist, wet, flooded
     - (1) Natural drainage: good, medium, poor
     - (2) Depth of water table............................feet

C. Forest description:

1. Origin: natural, artificial; seed, sprout, planted...
2. History: fires, lumbering; wind, snow, sleet, tapping for exudates
   - (*a*) Year:............................, ..., ..., ...
3. Pathological condition: good, medium, poor.
   - (*a*) Species attacked.............................. Injury to trunk, branch, leaf, root
     ....
4. Type name............................; all aged, even aged...
   - (*a*)

		Age	D.B.H.
Species	Percent	Avg. or Range	Avg. or Range
....	....	....	....
....	....	....	....
....	....	....	....
....	....	....	....

   - (*b*) No. of trees over....................in d.b.h. per acre....................(¼ acre, 57 ft. radius; ⅛ acre, 41.7 ft. radius; ⅒ acre, 37.3 ft. radius).
   - (*c*) Density of crown cover: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0.
   - (*d*) Underbrush: species ....
     ....
     amount..
     ....
5. Forest floor
   - (*a*) Ground cover: weeds, grass, bracken, briars, vines....................................
   - (*b*) Litter: kind..amount..
   - (*c*) Raw humus or duff: depth..
   - (*d*) Humus: depth..
6. Photographs: yes, no. Taken by..
7. Trees collected:..

† Prepare page 2 of this form for each site or forest. Underline descriptive words and fill in all blank spaces that apply. Use reverse of this form for additional notes.

TABLE 28. SHIPMENT DESCRIPTION—FIELD NOTES—*Continued*

Date..

Shipment No......................Species.......................................Project No......................

State.....................Co....................Twp....................Range...................Sec....................

D. Tree description:‡ Tree No...........................

1. Date sawed.................How removed from woods...................Date.................
2. Tree class: Open, dominant, codominant, intermediate, suppressed.
3. Origin: seedling, sprout. 4. Age at stump....................years.
5. D.B.H. o.b....................in. Total ht..................ft. Merch. ht..................ft. Top d.i.b....................
6. Stump ht..................in. Root swelling ht................in. Avg. diam. stump i.b....................in.
7. Crown: length...............ft., width...............ft., projection, ft. E................ W................N................S................
8. Foliage density: thick, medium, thin.
9. Lean: direction.............; 2, 4, 6.............degrees. Crook: form...........
10. Locate position and size of adjacent trees and stumps on diagram of concentric circles, assuming the tree to stand at the center and the intervals to be 5 (or 10) ft. Indicate d.b.h. and species by appropriate abbreviations.
11. Give approximate time of cutting any adjacent trees...........................
12. Photographs of standing tree...........................

E. Specimens shipped:

1. Herbarium material: leaves...................., fruit...................., flowers...................
2. Size of pieces and location in tree:

	Mark	Height above Ground of Lower End, ft.	Length, ft.	Diameters i.b., in.	
				Bottom	Top
First section	....	....	....	....	....
Second section	....	....	....	....	....
Third section	....	....	....	....	....
Fourth section	....	....	....	....	....
....	....	....	....	....	....
....	....	....	....	....	....
....	....	....	....	....	....

3. Defects: Kind...........................Extent...........................
4. Photographs of sections...........................

‡ Prepare page 3 of this form for each tree. Underline descriptive words and fill in all blank spaces that apply. Use reverse of this form for additional notes.

Preparation for Shipment. The bark will be left on each log, and care shall be taken to keep the bark intact. The ends of the logs shall be carefully painted to retard or prevent end drying and end checking.

Record shall be made of the shipment routing, bill of lading, kind of shipment, date of shipment, and condition of material when shipped. Record shall also be made of date of receipt of shipment at destination, its condition, and method of storage.

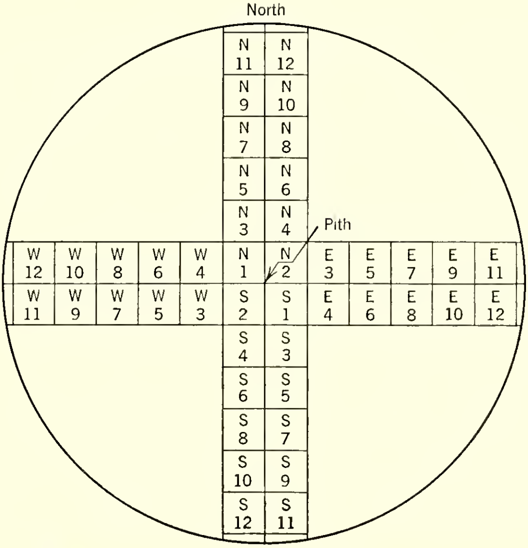

North
N 11
N 12
N 9
N 10
N 7
N 8
N 5
N 6
N 3
N 4
Pith
W 12
W 10
W 8
W 6
W 4
N 1
N 2
E 3
E 5
E 7
E 9
E 11
W 11
W 9
W 7
W 5
W 3
S 2
S 1
E 4
E 6
E 8
E 10
E 12
S 4
S 3
S 6
S 5
S 8
S 7
S 10
S 9
S 12
S 11

FIG. 89. Method of cutting up bolt and marking test sticks.

DISPOSITION

Storage of Logs at Destination. Material shall not be kept in the bolt or log form long enough to permit damage by checks, decay, stains, or insect attack. The logs shall be piled on skids, free from contact with the soil and shall not be stored where subjected to artificial heat. In addition they should preferably be protected from the sun.

Photographing, Sawing, and Final Marking. The top end of each *d* or *c-d* bolt shall be photographed. It is suggested that a rule be so placed on the log as to indicate the scale of the photograph and that the cardinal points be indicated on the cross section.

All bolts shall be marked on the top end into 2½-by-2½-in. squares as shown in Fig. 89 and sawed into nominal 2½-by-

2½-in. sticks. The letters N, E, S, and W indicate the cardinal points. When flitches are substituted for bolts, this same general marking and numbering scheme shall be followed insofar as it is applicable.

All test sticks shall bear the shipment number, the tree number, stick number, and bolt designation, to be known, respectively, as Shipment No., Piece No., Stick No., and Mark. Thus 400-1-N4*d* represents Stick N4 of Bolt *d*, Tree 1, Shipment 400.

Matching for Air-Dry Tests. In the tests made to determine the effect of air drying on strength, the sticks from the upper bolt of each 8-foot section shall be interchanged with those of the lower bolt of that section from the same tree to form two composite bolts, each composite bolt being complete and being made of equal portions of upper and lower bolts. The sticks from one of these composite bolts shall be tested unseasoned, and those from the other shall be tested after air drying. The sticks tested either unseasoned or air-dry shall be regarded as if they were from the same bolt.

The division of unseasoned and air-dry sticks shall be made according to the following schedule in which the numbers refer to stick numbers:

Selection of Sticks from *c* and *d* Bolts

Composite Bolt to Be Tested Unseasoned						
Lower bolt *c*	1		4, 5		8, 9	
Upper bolt *d*		2, 3		6, 7		10, etc.
Composite Bolt to be Air-Dried and Tested						
Lower bolt *c*		2, 3		6, 7		10, etc.
Upper bolt *d*	1		4, 5		8, 9	

The selection of sticks from other 8-foot sections of the tree to form composite bolts for green and air-dry testing will be made in accordance with this pattern.

Disposition of Sticks. Unseasoned material. The sticks (2½ by 2½ inches by 4 feet) to be tested unseasoned shall be kept in an unseasoned condition, while awaiting preparation for test, by being stored in a framed pit or other suitable container, where they shall be close piled and covered with damp sawdust or in some other suitable manner. As material is required for test, it shall be removed from this pit, or container, surfaced on all four sides to 2 inches by 2 inches in cross section, sawed to test size, and kept covered with a damp cloth, in an air-tight container at a temperature of about 70°F. (as nearly as practicable) until the time of test. Care shall be taken to avoid as much as possible the storage of unseasoned material in any form. Sticks to be tested in an unseasoned condition should usually not be sawed from the log form in quantities greater than are required to meet the testing demands for a few days to not more than 2 weeks, depending on the prevailing conditions.

Air-dry material. The ends of the sticks to be air dried (2½ by 2½ inches by 4 feet) shall be dipped in melted paraffin or other substance suitable to retard checking. The material shall be piled so as to have a space of at least ½ inch on each side of each stick to permit circulation of air. The material shall be stored in a place allowing free access of air, but protected from sunshine, rain, snow, and moisture from the ground. The sticks in drying shall not be subjected to artificial heat.

All of the sticks from each composite bolt to be air-dried shall be weighed when stored and at sufficiently frequent intervals thereafter to furnish accurate data on the progress of seasoning. No material shall be considered thoroughly air-dried and properly conditioned for testing until practically constant weight has been reached. (Wood absorbs and gives off moisture with changing atmospheric conditions; consequently, it never comes to absolutely constant weight.) When the material has reached approximate equilibrium, moisture sections 1 inch in length shall be taken from about 10 percent of the sticks to determine the actual moisture content. These moisture specimens shall be cut not less than 1 foot from the ends of the sticks and in such a way as to prevent any appreciable loss of material for testing. When thoroughly air-dry, the material shall be surfaced on four sides to 2 inches by 2 inches in cross section and tested.

With suitable drying facilities, the sticks may be kiln-dried rather than air-dried to shorten the drying period. If a kiln is used, drying will be continued until the sticks are reduced to a moisture content of approximately 12 percent. The dry kiln will be operated in accordance with best known practice for seasoning the particular species without reducing the strength of the wood, and kiln-drying defects such as collapse, casehardening, and honeycombing will be avoided. Kiln records will be kept of operating conditions during the entire period of drying. Maximum kiln temperature will not exceed 130°F.

After drying, sticks seasoned by either method will be stored preferably in a temperature- and humidity-controlled room at 75°F. and 64 percent relative humidity prior to testing. This procedure is intended to eliminate any moisture gradient remaining in the material and to achieve as nearly as possible a 12 percent moisture content.

Testing

ORDER, SELECTION, AND NUMBER

Order. The order of tests in all cases shall be such as to eliminate as far as possible from the comparisons the effect of changes in the specimen due to such factors as storage and weather conditions.

Selection. In case the material from a given bolt should be insufficient to furnish all the test specimens hereinafter required, the preferential order of mechanical tests to be used in selecting specimens shall be as follows: Static bending, compression parallel to grain, impact bending, toughness, compression perpendicular to grain, hardness, shear parallel to grain, tension perpendicular to grain, cleavage, and tension parallel to grain. Where a shortage of material exists, certain test specimens may be taken from the uninjured portion of the static- and impact-bending specimens remaining after test, providing proper care is used in the selection.

Only clear straight-grained material, free from decay and other defects, shall be used for the tests. However, small knots and other similar defects may be admitted in such specimens as static bending, when their location is such that it is certain they will not in any way influence the failure or otherwise affect the strength of the specimen.

Number of Tests for Each Bolt. Static bending. One specimen shall be taken from each pair of sticks. In each composite bolt a pair consists of two adjacent sticks equidistant from the pith, as W3 and W4, Fig. 89. Thus W3*d and* W4*c* constitute one pair of sticks to be tested unseasoned, and W3*c* and W4*d* the corresponding pair to be tested air-dry.

Compression parallel to grain. One specimen shall be taken from each stick. Load-compression curves shall preferably be taken on all of the specimens.

Impact bending. Eight specimens shall be taken from each bolt, selection being made from the sticks remaining after the static-bending material is obtained. Two specimens shall be selected from near the pith, two from near the periphery, and four representative of the cross section.

Toughness. Four toughness specimens shall be taken from the undamaged portion or end of each impact-bending specimen or its matching static-bending specimen. Thus a total of 32 toughness specimens will be selected from each bolt. From each group of four specimens taken from a single stick, two will be tested with the load applied to a radial face and two with the load applied to a tangential face.

Compression perpendicular to grain. One specimen shall be taken from each of 50 percent of the sticks selected for static bending.

Hardness. One specimen shall be taken from each of the other 50 percent of the static-bending sticks.

Shear parallel to grain. Twelve specimens shall be selected from the unused portion or ends of six sticks from which bending specimens have been selected. Two specimens shall be taken from near the pith, two from near the periphery, and eight that are representative of the average growth of the cross section of the bolt. One of each pair of specimens from the same stick shall be tested in radial shear (surface of failure radial) and the other in tangential shear (surface of failure tangential).

Tension perpendicular to grain. Twelve specimens shall be selected from six sticks in a manner similar to that for shear. One of each pair of specimens from the same stick shall be tested in radial tension (surface of failure radial) and the other in tangential tension (surface of failure tangential).

Cleavage. Twelve specimens shall be selected from six sticks in a manner similar to that for shear. One of each pair of specimens from the same stick shall be tested in radial cleavage (surface of failure radial) and the other in tangential cleavage (surface of failure tangential).

Tension parallel to grain. Six specimens shall be chosen, of which one shall be selected from near the pith, one from near the periphery, and four representative of the cross section.

Specific gravity and shrinkage in volume. Six specimens shall be obtained from the unused portion of bending or tension-parallel-to-grain sticks, selected so as to give one from near the pith, one from near the periphery, and four representative of the average growth of the cross section of the bolt. These specimens shall be selected only from the sticks to be tested in an unseasoned condition.

Radial shrinkage. Four specimens shall be obtained from each *d* bolt and if possible from the upper bolt of each 8-foot section selected at other heights in the tree. They shall be cut from the "sectors" or "quadrants" remaining after sawing (Fig. 89) or from disks cut from near the end of the bolt. When a disk is used, care must be taken to see that it is unseasoned and has not been affected by shrinking and checking which is common near the end of the bolt. The specimens shall not be surfaced. Radial-shrinkage specimens shall be cut with their greatest dimension in the radial direction. Two shall be taken from the heartwood, and the other two from near the periphery. When possible, the second pair shall consist entirely of sapwood.

Tangential shrinkage. Four specimens shall be obtained from each *d* bolt and if possible from other bolts, as described in the preceding paragraph. They shall be selected at the same time and in a manner similar to radial-shrinkage specimens, except that the greatest dimension shall be in a tangential direction. The specimens shall not be surfaced. Two shall be taken from the heartwood, the other two from near the periphery, and when possible they shall consist entirely of sapwood. The heartwood and the sapwood specimens shall be taken adjacent to the respective specimens selected for radial shrinkage.

GENERAL INSTRUCTIONS

Photographs of Sticks. Four of the bending sticks from each species shall be selected for photographing, as follows: two average growth, one fast growth, and one slow growth. These sticks shall be photographed in cross section and on the radial and tangential surfaces.

Control of Moisture Content. As previously specified (Disposition of Sticks—Air-Dry Material), sticks for test in the air-dry condition shall be brought to practically constant weight before test and if necessary reconditioned to constant weight after the final preparation of test specimens. Tests shall then be conducted in such a manner that large changes in moisture content will not occur. (For instance, in ordinary heated rooms the relative humidity is often below 30 percent. If wood that has been air-dried to practically constant weight is brought into such a room, a considerable and rather rapid drying out will occur.) To prevent such changes, the testing room and rooms for the preparation of test specimens should preferably have some means of humidity control.

Control of Temperature. All tests (except those specifically designed to study effects of temperature) will be made at temperatures of 70 to 80°F. Temperature at time of test will be recorded.

Record of Heartwood and Sapwood. The estimated proportion of sapwood present shall be recorded for each test specimen.

PROCEDURE—MECHANICAL TESTS

The methods that shall be used in making the various mechanical tests are discussed in detail in Part 4 of the body of this text (see Description of Tests, pages 293–339). This procedure conforms with that outlined in Standard methods of testing small clear specimens of timber, Serial Designation: D143-48, 1948 *Book of Standards,* American Society for Testing Materials, Philadelphia, Pt. II.

PROCEDURE—PHYSICAL TESTS

Specific Gravity and Shrinkage in Volume. The specific gravity and shrinkage-in-volume tests shall be made on 2-by-2-by-6-inch unseasoned specimens, surfaced on all four sides and sawed smooth on the ends. Both determinations shall be made on the same block.

The actual cross-sectional dimensions and length of each specimen shall be measured and entered on a suitable data card, together with information on the number of rings per inch, percent of sapwood, and, when possible, percent of summerwood.[3] A carbon impression of the end of the unseasoned specimen shall be made on the back of the data card; in like manner, a carbon impression of the same end shall be made after the block has been oven-dried.

---

[3] See Standard methods of testing small clear specimens of timber, footnote 1, Fig. 45 of Appendix.

Each specimen shall be weighed when unseasoned, and the volume shall be determined by the immersion method.[4] After immersion all specimens shall be open piled and allowed to air-season under room conditions until approximately constant weight is attained. They shall then be open piled in an oven and dried at 100°C. until constant weight is reached. Each block shall then be weighed and, while still warm, immersed in a hot paraffin bath, care being taken to remove it quickly to insure a thin coating. The volume of each paraffin-coated specimen shall then be determined by immersion as before.

All data on weights and volumes of each test specimen shall be entered on the proper data card, together with calculated values for specific gravity, weight per cubic foot, moisture content, and shrinkage in volume (based on unseasoned volume).

Radial and Tangential Shrinkage. The radial- and tangential-shrinkage determinations shall be made on unseasoned specimens, 1 inch thick, 4 inches wide, and 1 inch long. The samples for use in determining radial shrinkage shall be cut with the width in the radial direction; those for tangential shrinkage with the width in the tangential direction. Specimens shall not be surfaced.

Each specimen shall be measured across the dimension (4 inches) in which the shrinkage is to be determined and weighed, both when unseasoned and after subsequent oven drying. A micrometer of required accuracy (0.001 inch), is suitable for making measurements. All measurements and weights shall be recorded on a suitable data card, together with information on number of rings per inch, percent of sapwood, and, when possible, percent of summerwood.[5]

In drying the specimens, they shall first be open piled and allowed to air-season under room conditions until approximately constant weight is attained. They shall then be open piled in an oven and dried at 100°C. until constant weight is reached.

---

[4] In the immersion method, volume is conveniently determined using metric units by weighing the quantity of water displaced by the specimen. The numerical value for weight in grams of the water displaced (the difference between weight of a container of water before and after immersion of the specimen) is equivalent to the volume of the specimen in cubic centimeters.

[5] See Standard methods of testing small clear specimens of timber, footnote 1, Fig. 46 of Appendix.

The moisture content of each unseasoned specimen and its percent of shrinkage in the radial or tangential direction (based on unseasoned width) shall be computed and entered on the data card.

Moisture Determination. The standard procedure for making moisture determinations is discussed in detail under Timber Testing (see pages 280–2).

TOLERANCES

Weights. The weight of test specimens and of moisture samples shall be determined to an accuracy of not less than 0.2 percent.

Measurements. Measurements of test specimens shall be made to the nearest 0.01 inch, except in the cross-sectional dimensions of tension parallel to grain and toughness specimens and the radial and tangential dimensions of linear-shrinkage specimens for which measurements shall be taken to the nearest 0.001 inch.

Testing-Machine Speed. In no case shall the testing machine speed used vary more than 25 percent from that specified for a given test. The load shall be applied continuously, without interruption, at the required speed throughout the test. Crosshead speed is defined as the no-load (free-running) speed for testing machines of the mechanical-drive type and as loaded crosshead speed for machines of the hydraulic loading type.

CALIBRATION

All apparatus used in obtaining data shall be calibrated at sufficiently frequent intervals to insure accuracy.[6]

[6] See Standard methods of verification of testing machines, Serial Designation: E4-47T, 1947 *Book of Standards,* Am. Soc. Test. Mat., Philadelphia, Pt. II.

Index

Abrasion, 72
Accidental overloading, 212
Age of tree, effect on properties, 170
Aircraft parts, reference to tests, 343–4
Air drying, effect on strength, 187–8
American lumber standards, 206, 221–35
Annual rings, *see* Growth rings
Apparatus, testing, *see* Test procedure

Bankia, 142
Bark pockets, 126, 129
Basic-stress values, 207, 212–19
  adjustment, for density, 209–10
    for duration of load, 210–11, 219–20
    for overloading, 212
    for rate of growth, 210
    for variability in clear-wood strength, 208–10
Beams, forms of, 38–9
  strength of, 38–41, 64–6
    see also Bending strength
  stresses in, 41–8
  working stresses for, 248–68
Bending, relation to thickness, 68
  stresses, 38–48
Bending strength, 38–66
  effect, of defects, 82–3, 98, 105–08, 118–19, 122–4, 128–9, 225–33, 236–46, 248–53
    of duration of stress, 203
    of extractives, 130, 196–9
    of incising, 193, 195–6
    of moisture, 183–7
    of steaming, 193, 195
    of temperature, 189–91
  relation to density, 153–7
Bending strength, values for, 10–25
  variation in, 174, 208–09
Bird peck, 139–40
Black streak, 137–9
Blue stain, 115–16, 119
Boiling, effect on wood, 48, 191
Bow as a defect, 131
Box beams, 257–9, 263, 266
Boxed-heart timbers, 151
Boxes and crates, reference to tests, 344–5
Brashness, 6, 48–50, 118–19, 122–3, 190–1, 298
Brittleness, *see* Brashness
Burls, 147–8

Cantilever beam, 39
Casehardening, 94, 132
Ceratostomella spp., 115
Checking of wood, 83–98, 132–3, 230–2
Checks, effect on strength, 97–8, 230–2, 242–3
  end, 94–6
  heart, 97
  internal, 132–3
  measurement of, 231–2
  star, 97
  surface, 93–4
Chelura, 142
Chestnut blight, effect on strength, 200
Cleavage resistance, 10–25, 72–3
  test, 318–20, 363
Collapse, 133–4
Columns, effect of knots on, 229, 239
  intermediate, 269–70, 272
  long, 270–2
  round, 272
  short, 268–9, 272

Columns, short, failures in, 30–4, 50
  strength of, 268–72
  tapered, 272
  working stresses for, 248–53
Combined bending and axial loads, 273–4
Compression, endwise, *see* parallel to grain
  failures, 30–4, 48, 51, 120–2
    effect on strength, 122
  parallel to grain, 27–34
    test, 304–09, 363
    working stresses for, 248–53
  perpendicular to grain, 27
    test, 309–12, 363
    working stresses for, 248–53
  sidewise, *see* perpendicular to grain
  wood, 85, 122–5, 233–4
    strength of, 122–4
Compressive strength, 27–34
  effect, of defects, 82–3, 98, 107–08, 119, 122–4, 130
    of extractives, 130, 197–8
    of incising, 195
    of moisture, 183–5, 217
    of steaming, 48, 193, 195
    of temperature, 189, 191
  relation of density to, 153–7
  values for, 10–25
Compressometer, 304, 307, 309–10, 312
Conifers, density–rate of growth relations, 164–6
  estimation of density in, 161–2, 164
  structure of, 160
Continuous beams, 39
Creosote, effect on strength, 192–4
Crook as a defect, 131
Crossarms, references to tests, 343
Cross breaks, 122
Cross grain, 98–108
  detection of, 101–04
  effect on strength, 105–08, 240
  measurement of, 104–05
Crushing strength, 10–25, 27–34
Crushing strength, *see also* Maximum crushing strength
Cupping of lumber, 131–2

Dead timber, strength of, 200
Decay, 109–15, 117–19, 199
  bearing on working stresses, 247, 254
  effect on strength, 117–19
Defects, 78–152, 223–33, 235–46
  bearing on working stresses, 235–46
  effect on strength, 78–152, 235–46
  powder post, 136–7
  prevalence in heartwood, 198–9
  relation to stiffness, 246
  seasoning, 83–6, 93–8, 131–4
Definitions, 3–7
Deflection of beams, 67–8, 264–6
Deflectometer, 293–4, 297
Density, 152–66
  effect, of growing conditions, 163–6, 170–8
    of moisture content, 159, 180–2
    of position in tree, 167–70
    on shrinkage, 94–5
  methods of estimating, 158–66
  of heartwood and sapwood, 198–9
  of wood substance, 153
  rule, 161–2, 164, 210, 233–5
  specifications, 233–5
Density–strength relations, 153–8
Diagonal grain, 103–04
  see also Cross grain
Diffuse-porous hardwoods, 161, 163, 165–6
Dip grain, 99, 128
Diplodia spp., 115
Dote, 109
Douglas fir, close-grained, 164, 235
  dense, 161–2, 164, 233–5
Doze, 109
Drying methods, effect on strength, 93–6, 187–8
Dry rot, 113, 115
Durability of wood (Decay resistance), 111–12, 199–200
  bearing on working stresses, 254

Duration of stress, effect of, 203, 210–11

Early wood, *see* Springwood
Elasticity, 5–6
  modulus of, *see* Modulus of elasticity
Elastic properties of wood, 10–25, 66–8, 73–5
Elastic resilence, 6, 57–64, 69–70
  formulas for, 292–3, 298, 303–04
Endoconidiophora spp., 115
Endurance limit, 204
Euler, formula, 271
  load, 28
Exposure, bearing on working stresses, 247–54
Extractives, effect, on durability, 111–12, 199
    on moisture-content determination, 179, 281–2
    on strength, 130, 197–8
    on weight of wood, 158–9
Extreme fiber in bending, working stresses for, 248–53

Factor of safety, *see* Reduction factor
  actual, 216
Failures, bending, 48–53
    effect of temperature, 191
  compression, parallel to grain, 30–4
    perpendicular to grain, 27
  shearing, 33–6, 38
  tension, parallel to grain, 26
False rings, 137
Fastenings, references to tests, 346–7
Fatigue, 204
Fiber-saturation point, 85, 93, 183, 185–6
Fiber stress at proportional limit, 5, 27, 29, 66, 69
  formulas, 66, 292–3, 298, 303, 309, 312
Fibrils, orientation of, 84–5, 93, 124, 178–9
Field selection for mechanical testing, 354–9
Fire-killed timber, strength of, 200
Flexibility, 5, 69
Flexure formula, 41, 46, 65, 254, 260
Floccosoids, 148
Fomes laricis, 117
Fomes pini, 117–18, 148
Form factor, 254–5, 257–8, 260
Formulas, bending stress, 41, 46, 65, 254–5, 292–3, 298, 303–04
    I beams, 257–8
    laminated beams, 259–61
  column, 268–71
  deflection in beams, 67–8, 264–5
    I beams, 266–7
    laminated beams, 267–8
  elastic resilence, 292–3, 298, 303–04
  Euler, 271
  fiber stress at proportional limit, 292–3, 298, 303–04, 309, 312
  flexure, *see* Bending stress
  fourth-power parabolic, 269–70
  horizontal shear, 46–7, 262
    I beams, 263
    laminated beams, 263–4
  maximum crushing strength, 309
  modulus of elasticity, 7, 67, 292–3, 298, 303–04, 309
  modulus of rupture, 65, 292–3, 298
  shearing strength, 37, 292–3, 298, 317
  testing machine speed, 285
Frost, cracks, 145
  rings, 145
  splits, 145
    effect on strength, 145–6
Fungi, dry-rot, 113, 115
  wood-destroying, 108–15, 117–19
  wood-inhabiting, 107–19
  wood-staining, 115–17, 119

Grades, structural, *see* Structural lumber, grades
Grading rules, basic provisions, 223–35
  beams and stringers, 222, 227–9, 231–2

Grading rules, defect limitations, 223–33, 236–46
  density specifications, 233–5
  factors involved in establishing, 220–2
  heartwood and sapwood provisions, 233
  joist and plank, 221, 225–7, 231–2
  moisture effects, 241–5, 247–54
  posts and timbers, 222, 229, 231–2
  rate of growth specifications, 235
Grain, variation in, 98–100
    see also Diagonal, Cross, and Spiral grain
Graphium spp., 115
Growth, conditions, effect of, 170–9
  rate, effect on density, 163–6
  rings, 160
    false, 137
    relation to failures, 26, 33–4, 37
    secondary, 137
Grub holes, 135

Hankinson formula, 274–5
Hardness, 10–25, 71–2
  test, 312, 314, 363
Hardwoods, diffuse-porous, 161
  effect of rate of growth, 163–6
  ring porous, 161
  structure of, 161
Heart center, 151
Heartwood and sapwood, 196–200
  durability, 112, 199
  moisture content, 180, 199
  relative strength, 198–9
Heat, effect on bending, 48, 191
Height of drop in impact bending, 58–63, 69, 302–03
  effect of cross grain, 107–08
Honeycombing, 84, 132–3
Hooke's law, 3
Horizontal shear, *see* Shear, horizontal

I beams, 257–9, 263, 266–7
Impact, 56–64
  bending test, 299–304, 363
Incising, effect on wood, 193, 195–6
Indented rings, 148–9
Insect injuries, 134–9
Interlocked grain, 99
Isotropic material, 8

Joists, working stresses for, 248–53

Kiln drying, effect on strength, 187–8
Knots, 78–83, 223–9
  effect, on strength, 81–3, 235–9
    on weight of wood, 159
  encased, 80
  intergrown, 80
  measurement of, 223–9
  oval, 79
  round, 79
  spike, 79

Laboratory tests, advantages of, 1
Laminated construction, 259–61, 263–4, 267–8, 272–3
Late wood, *see* Summerwood
Lightning rings, 146–7
Limit of proportionality, 5
Limnoria, 142–3
Live versus dead timber, 200
Load-deformation curve, 4, 70–1
Loading, center, 40, 52, 289
  impact, 56–7, 64
  long-time effect, 203, 211
  normal conditions of, 220
  static, 55
  sudden, 55–6
  third point, 40, 52, 286, 289
  uniform, 40, 52
Loads, application of, 55–7, 64
  concentrated, 52
  dead, 53–4
  immediate, 53
  live, 53–4
  moving, 53
  permanent, 53–4
  rolling, 53
  safe, 54–5
  uniform, 52
Lyctus beetles, 136–7

Marine borer injury, 140–4
  species resistant to, 144
Material for tests, *see* Test specimens
Maximum crushing strength, 10–25, 29
  effect of cross grain, 105, 107
  formula for, 309
Mechanical properties, definition of, 1
  factors affecting, 77–204
    references to, 204–05
  list of, 2, 354
  references to, 75–6
Merulius lachrymans, 115
Microstructure of wood, effect on properties, 178–9
Mineral streaks, 139
Mine timbers, references to tests, 343
Mistletoe injury, 144–5
Modulus of elasticity, 6–7, 10–25, 29, 66–7, 73–5
  see also Stiffness
  effect of slope of grain, 107–08
  formulas for, 292–3, 298, 303–04, 309
  in table of working stresses, 246, 248–53
Modulus of rigidity, 74–5
Modulus of rupture, 10–25, 64
  see also Bending strength
  application to working stresses, 215–16, 235–6
  effect, of cross grain, 107–08
    of duration of stress, 203, 210–11
  formulas for, 64–5, 292–3, 298
  variation in, 174, 208–09, 215–16
Moisture, free, 85
  hygroscopic, 85
  in relation to decay, 111–14, 199
  reabsorption, relation to strength, 188
Moisture content, 10–17, 85, 179–88
  determination, 179–80, 280–1
    distillation method of, 179, 281–2
  distribution, large timbers, 182
Moisture content, effect, on failures, 26, 31–3, 37, 49–51
    on strength, 183–7, 207–08
    on weight of wood, 87–92, 159, 179–82
    on working stresses, 207–08, 241, 245, 247
  equilibrium, 180–1
  relation to density, 157–9, 180–2
  seasonal variation, 201–02
Molds, 116–17
Moment, bending, 41–5, 65, 254–7
  of inertia, 45, 65, 265
    I beams, 257–9, 266
    laminated beams, 260–1, 267
  statical, 46–7, 262–3

Natural shape and size, 3
Neutral axis, 39–40
Neutral plane, 39–40
Nomenclature of American woods, 349–53
Normal loading conditions, 219–20, 247

Orthotropic material, 8
Overloading, bearing on working stresses, 212, 216

Parasitic plant injuries, 144–5
"Pecky" wood, 109, 223
Permanent set, 5–6
Phoradendron flavescens, 144
Pine, southern, 165–6, 175–6
    dense, 161–2, 164, 234–5
Pinholes, 135
Pitch, 129–31
  effect on strength, 130
  pockets, 126–9, 137
    effect on strength, 128–9
  seams, 128
  streaks, 129
Pith, 149, 151
  flecks, 138–9
Plasticity, 6
Plywood, references to tests, 345–6
Poisson's ratios, 74–5

Poles and piling, references to tests, 342–3
Polyporus schweinitzii, 117–18
Position in tree, effect on properties, 167–70
Powder post damage, 136–7
Preservative treatment, 191–6
Proportional limit, 4, 5
  fiber stress at, 10–25, 27, 29, 66, 69
  work to, 6, 69–70
"Punky" wood, 109

Rate of growth, effect on strength, 163–6
  rule, 164, 210, 234–5
Razoumofskya spp., 144
Red radial streak, 149
Reduction factor, 54–5, 207, 209, 211–12, 215–18
Redwood, close-grained, 164, 235
References, 75–6, 204–05, 275–7, 340–8
Relaxation, 203
Resilience, 6, 57, 293, 304
  elastic, *see* Elastic resilience
Resin, 125–31
  effect, on strength, 130
    on weight of wood, 130–1, 158–9
Rind gall, 97
Ring-count rule, 164, 210, 234–5
Ring distortions, 137
Ring-porous hardwoods, 161–6
Rot, 109–15
  brown, 111
  dry, 113, 115
  white, 111
Round timbers, strength of, 256–7, 272
Rupture, modulus of, *see* Modulus of rupture

Safe load, 54
Safety, factor of, *see* Reduction factor
Sap stain, 115–17, 119
  effect on strength, 119
Sapwood, 112, 180, 196–200, 233
Sapwood, durability of, 112
  relation to growing conditions, 197
Seasoning defects, 83–98, 131–4, 230–2
Season of cutting, effect of, 201–02
Second growth, 170, 172, 176–7
Set, 5–6, 265
Shake, 83–4, 96–8
  cup, 84
  effect on strength, 97–8, 242–4
  heart, 83, 97
  measurement of, 230–1
  ring, 84, 96
  star, 83, 97
  wind, 96
Shear, 4, 35–8
  horizontal, 36, 39–40, 46–8, 51–2, 218
    calculation of, 46–8, 262–4
    formulas for, 46–7, 262, 292–3, 298
    working stresses for, 248–53
  oblique, 35, 38
  parallel to grain, 35–8
    see also Shear, horizontal
    formula for, 37, 317
    test, 314, 316–17, 363
  perpendicular to grain, 35–7
  rolling, 35
  vertical, 46
Shearing strength, 10–25, 35–8
  effect, of defects, 37, 82, 98, 105, 107, 128, 133, 138, 145–6, 242–4
    of incising, 195–6
    of moisture, 185
Shipping containers, references to tests, 344–5
Shipworms, 141–4
Shock, 56–64
Shock-resisting ability, 10–25, 58–63, 68–71
  see also Toughness
Shrinkage, 84–96, 200
  equations for estimation of, 95
  method of determination, 364–7
Side-cut timbers, 151

Simple beam, 39, 42–5
Slip plane, 30, 120
Slope of grain, 104–08
Span, 65–8
Specific gravity, 10–25, 152–8, 167–8, 170–1
  see also Density
  bases for computation, 157–8
  effect, of decay and stain, 118–19
    of temperature, 191
  method of determination, 364–6
Specific gravity–strength relations, 153–7
Speed of testing machine, 285–6
  equations for determination of, 285
Sphaeroma, 142
Spiral grain, 100–03, 105–07
  see also Cross grain
  artificial, 104
Splits, 84, 230–1
Springwood, 8
Static-bending tests, 286–99
  large beams, 286–93
  small beams, 293–9
Steaming, effect on wood, 6, 48, 190–3
Stiffness, 5, 66–8
  bearing on column strength, 268–71
  effect, of density, 153–7
    of dimensions of beams, 67–8
    of knots, 81–2, 246
    of moisture, 183–5
  of compression wood, 123–4
Strain, 3
Strength, 2
  effect, of age of tree, 170
    of conditions of growth, 170–8
    of defects, 78–152
    of density, 152–7
    of duration of stress, 203
    of extractives, 129–30, 197–8
    of incising, 193, 195–6
    of method of drying, 187–8
    of microstructure of wood, 178–9
Strength, effect, of moisture, 183–7
    of position of tree, 167–70
    of preservative treatment, 191–6
    of rate of growth, 163–6
    of reabsorbed moisture, 188
    of season of cutting, 201–02
    of steaming, 190–3
    of summerwood, 159–63
    of temperature, 188–91
    of turpentining, 130–1
  of compression wood, 123–4
  of heartwood and sapwood, 197–9
  of live and dead timber, 200
  ratios, 235–46
  values, adjustment for moisture, 185–7
Stress, basic, *see* Basic-stress values
  compound, 4
  compressive, 4, 39
  external, 3
  impact, 56–7, 64
  in beams, 39–48
  internal, 3
  shearing, 4, 35–8
  splitting, 26, 72–3
  tensile, 4
  working, *see* Working stresses
Stress–strain diagram, 4, 70
Structural axes of wood, 8–9
Structural grading rules, 223–35
  see also Grading rules
Structural lumber, grades, 206–07, 220–2, 236–46, 248–53
  references to tests, 341–2
  standard dimensions, 222
  use classification, 221–2
Structure of wood, 8–9, 160–1
  effect on shrinkage, 85–6 93, 95
Summerwood, 159–65

Temperature, effect, on wood, 188–93
    on wood-destroying fungi, 114–15
Tensile strength, 9, 26
Tension, 9

Tension, effect of defects, 9, 81–2, 97–8, 105, 122–3
  failures, 48–50, 123
  parallel to grain, 9, 26
    test, 319–21, 363–4
  perpendicular to grain, 10–27
    test, 317–18, 363
Teredo, 142–3
Termites, 135–6
Testing machine, calibration, 367
  capacity, 284–5
  impact, 299, 301
  speed of, 285–6, 367
  static, 282–5
  toughness, 321–4, 339
Test procedure, cleavage, 318–19
  compression, parallel to grain, 304–09
    perpendicular to grain, 309–12
  hardness, 312–14
  impact bending, 299–304
  moisture content, 281–2
  shear parallel to grain, 314–17
  shrinkage, 365–7
  specific gravity, 365–6
  static bending, large beams, 286–93
    small beams, 293–9
  tension, parallel to grain, 319–21
    perpendicular to grain, 317–18
  toughness, 321–4, 339
Tests, description of, 286–324, 339–40
  see also Test procedure
  impact, increment drop, 69, 299–304
    single drop, 69–70, 321–4, 339
    value of, 321, 324, 339
  list of, 354
  miscellaneous, references, 347–8
  on small specimens, references, 340–1
  on structural timbers, references, 341–2
  purposes of, 279–80
Test specimens, collection, 354–9
  form, 278
Test specimens, marking, 359–60
  matching for air-dry tests, 360
  selection for tests, 362–4
  size in relation to purpose of tests, 279–80
  storage of, 359–62
Timber sizes, beams and stringers, 222
  joist and plank, 221
  posts and timbers, 222
Timber testing, 278–340
  references to, 340–8
Torsion, 70–1
Toughness, 68–71
  effect, of decay and stain, 117–19
    of extractives, 130, 197–8
    of method of drying, 188
    of moisture, 183–5
    of slope of grain, 107–08
    of temperature, 190–1
  of compression wood, 124
  relation to density, 154–7
  test, 321–4, 339
Turpentining, effect on strength, 130–1
Twist as a defect, 131

Universal testing machine, 282–5

Variability of wood, 2–3, 77, 155, 171–8, 208–10
Virgin growth, 166, 172

Wane, 233
Warping of wood, 131–2
Wavy grain, 99
Wearing ability, 72
Weight, per cubic foot, 152
    values for, 87–92
  relation to strength, 158–9
"White ants," 135–6
Winter-cut timber, advantages, 201–02
Wood, preservatives, effect on strength, 191–2
  substance, density of, 153
Wood-destroying fungi, 109–15, 117–19

Wood lice, 142
Wood-staining fungi, 115–16, 119
Work, 6, 56–7, 69
  see also Resilience
  to maximum load, 6, 10–25, 70
    see also Toughness
  to proportional limit, 6, 10–25, 57–63, 69–70
  total, 10–25, 70
Working plan, 278, 353–67
Working stresses, 206–75
  adjustment, for defects, 223–46
    for duration of load, 247
    for exposure, 247, 254
Working stresses, adjustment, for moisture effects, 241, 245, 247
  derivation, 207–19, 235–46
  for columns, 268–72
  references to, 275–7
  table of, 248–53

Xylotria, 142

Young's modulus, *see* Modulus of elasticity

Zinc chloride, effect on strength, 192

ARCHITECTURE & FINE ARTS LIBRARY

Date Due

Due	Returned	Due	Returned
JAN 2 6 2004	JAN 2 9 2004		

Form #0060

Mechanical properties of wood afa
620.12W246m
3 1262 02172 0080

LAD